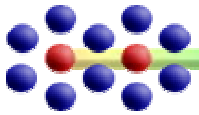
MRS Meeting, April 1-5, 2002, San Francisco

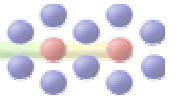


COUPLED-CAVITY STRUCTURES IN PHOTONIC CRYSTALS

MEHMET BAYINDIR
EKMEL OZBAY

Department of Physics, Bilkent University, Turkey

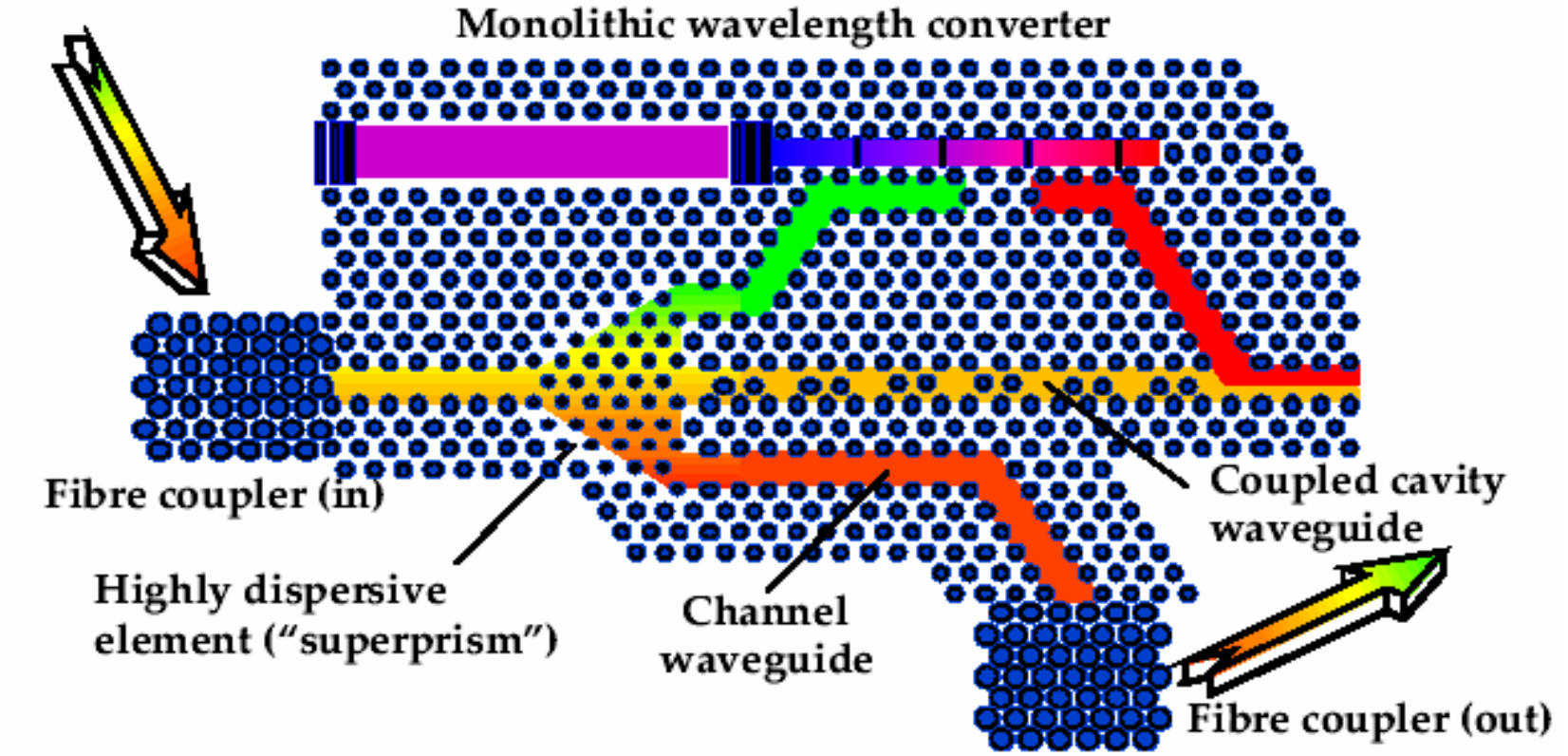
OUTLINE



- Motivations
- Underlying Physics
  - Investigation of coupled-cavity structures: FDTD, TMM, experiment, and tight-binding approximation
    - Localized cavity modes
    - Eigenmose splitting
    - Photonic molecules
  - Observation of a new type of waveguiding mechanism: Coupled-cavity waveguides (CCWs)
- Possible Applications
  - Waveguides, waveguide bends, splitters, switches
  - WDM: adding or dropping a selective wavelength or band
  - Strong enhancement of the spontaneous emission
  - Increasing efficiency of nonlinear processes
  - Dispersion compensators
- Summary

MOTIVATIONS

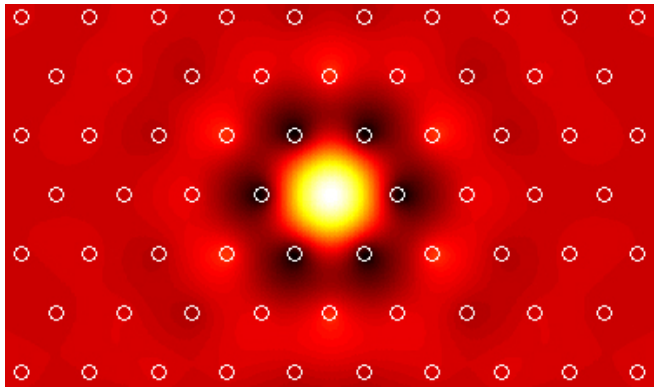
PHOTONIC INTEGRATED CIRCUIT

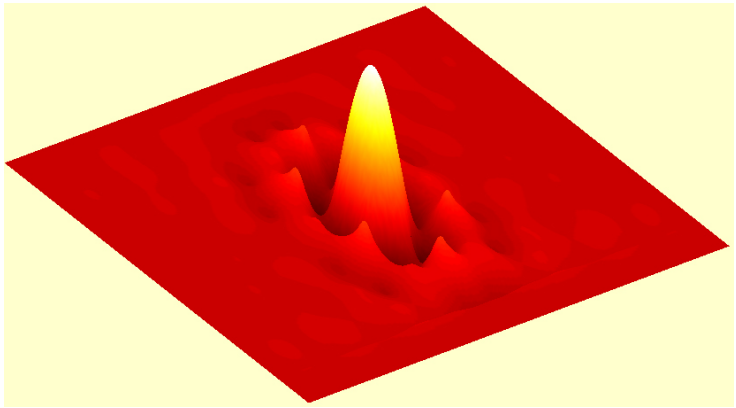


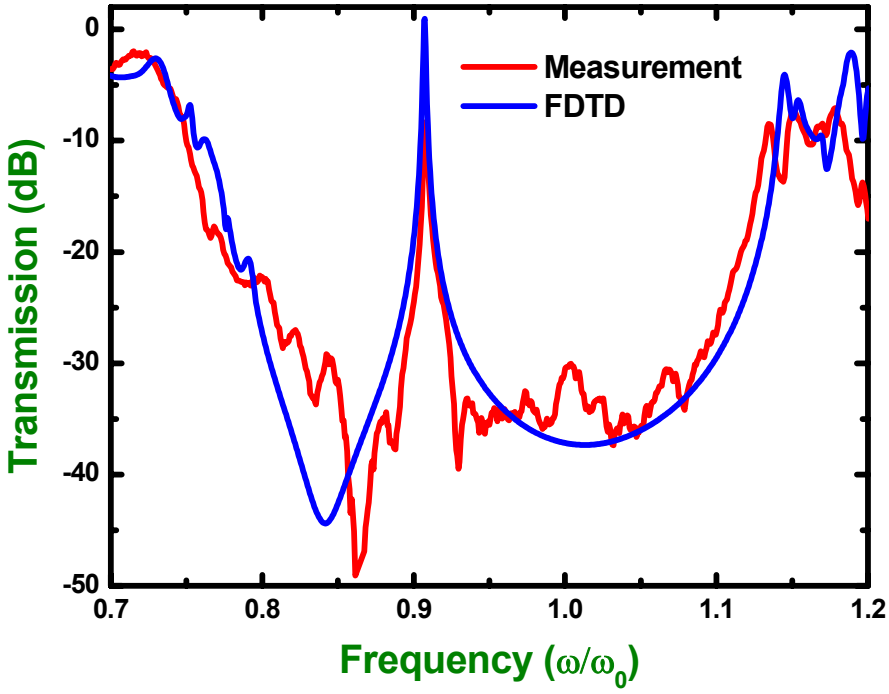
[from Krauss' paper]

TO CONSTRUCT ALL OPTICAL COMPONENTS ON A SINGLE CHIP

2D PHOTONIC CRYSTALS: LOCALIZED CAVITY MODE







$$\nabla \times \left[\nabla \times \mathbf{E}_{\Omega}(\mathbf{r})\right] = \left(\Omega_0 / c\right)^2 \varepsilon_0(\mathbf{r}) \mathbf{E}_{\Omega}(\mathbf{r})$$

Observation of strongly localized cavity modes within the photonic band gap analogous to acceptor impurity state in semiconductors

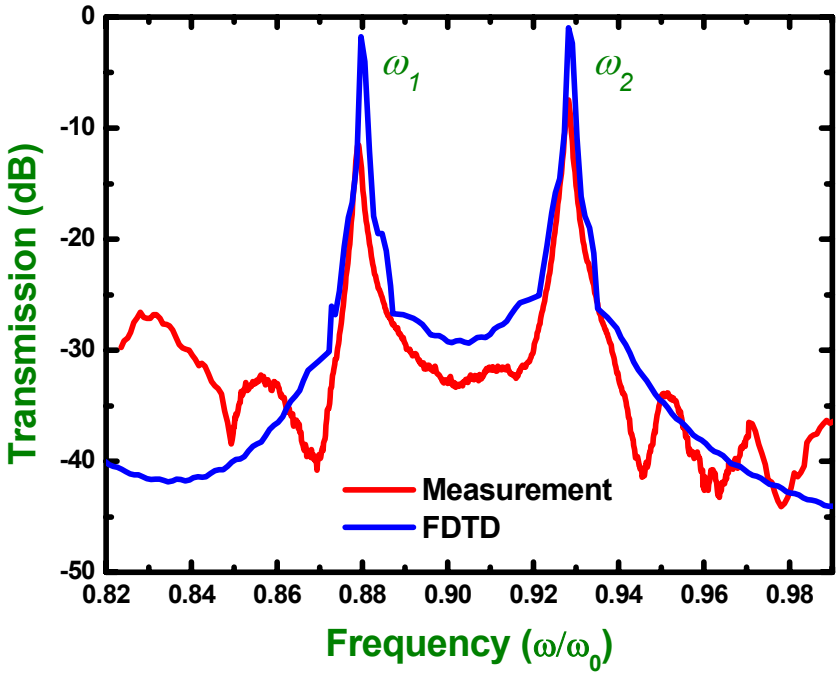
EIGENMODE SPLITTING

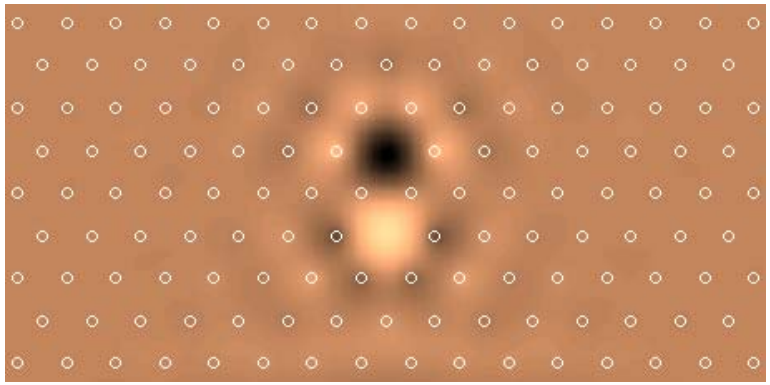
$$\mathbf{E}_{\omega}(\mathbf{r}) = A\mathbf{E}_{\Omega}(\mathbf{r}) + B\mathbf{E}_{\Omega}(\mathbf{r}-\Lambda)$$

Linear combination of the individual evanescent cavity modes

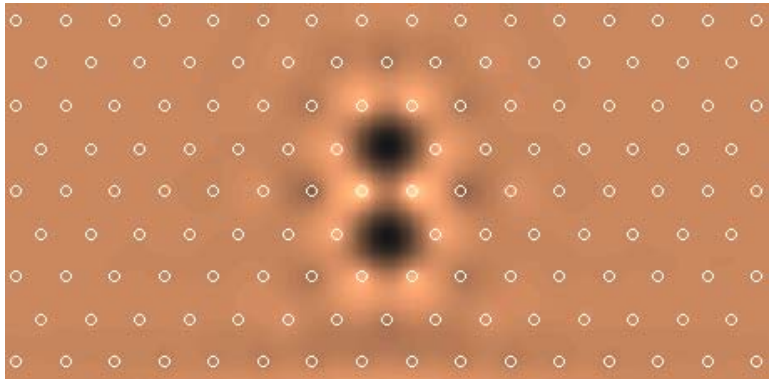
$$\nabla \times [\nabla \times \mathbf{E}_{\omega}(\mathbf{r})] = (\omega/c)^2 \varepsilon_0(\mathbf{r})\mathbf{E}_{\omega}(\mathbf{r})$$

$$\omega_{1,2} = \Omega\sqrt{\frac{1 \pm \beta}{1 \pm \alpha}}$$





$$E_{\omega_1} = \frac{E_{\Omega}(r) - E_{\Omega}(r-\Lambda)}{\sqrt{2}}$$



$$E_{\omega_2} = \frac{E_{\Omega}(r) + E_{\Omega}(r-\Lambda)}{\sqrt{2}}$$

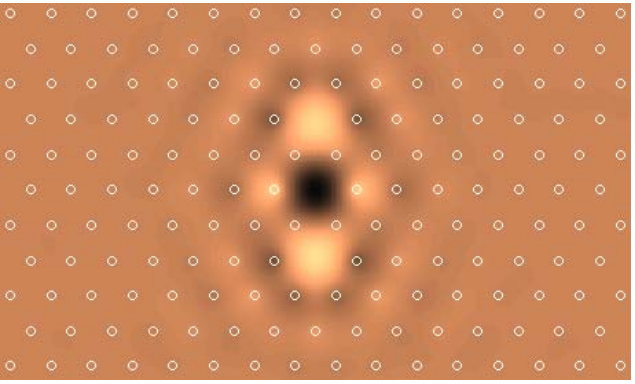
Formation of bonding and antibonding photonic modes

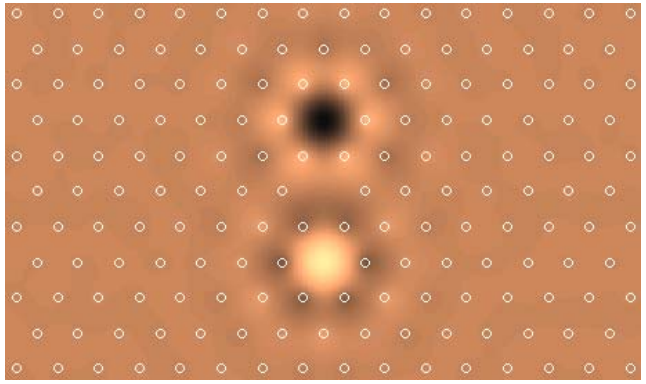
PHOTONIC MOLECULES

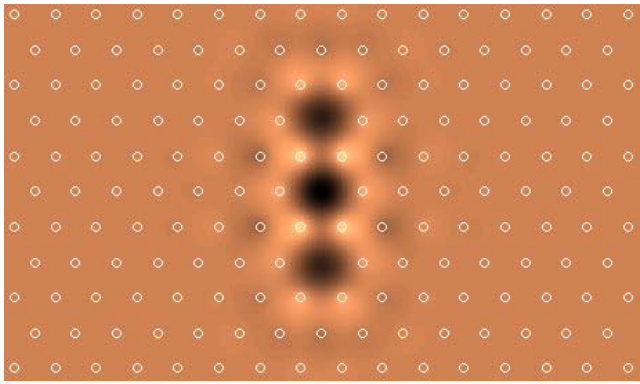
$$E_{\Gamma_1} = \frac{E_\Omega(r) - \sqrt{2}E_\Omega(r-\Lambda) + E_\Omega(r-2\Lambda)}{2}$$

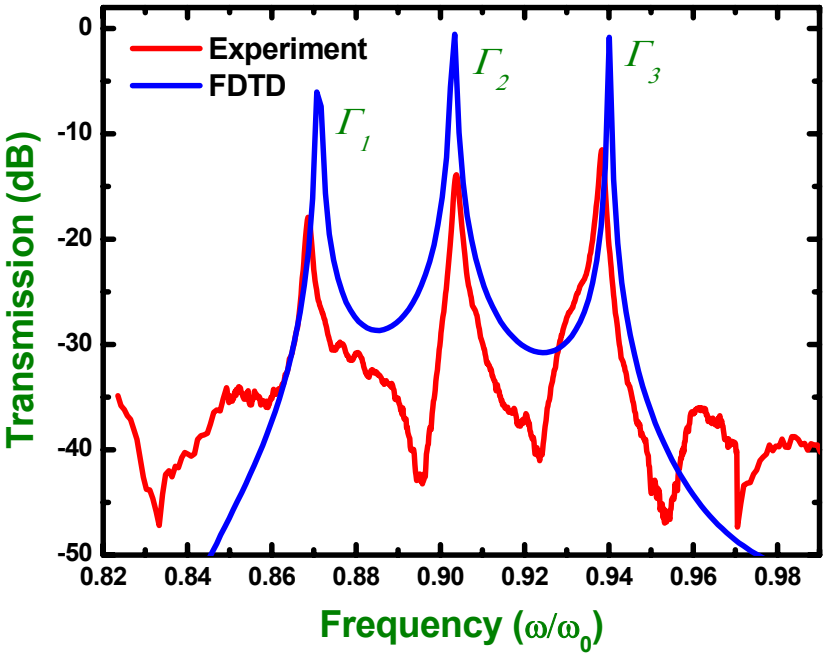
$$E_{\Gamma_2} = \frac{E_\Omega(r) - E_\Omega(r-2\Lambda)}{\sqrt{2}}$$

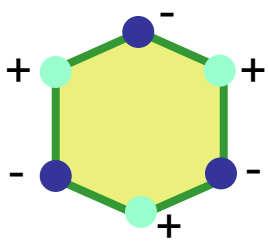
$$E_{\Gamma_3} = \frac{E_\Omega(r) + \sqrt{2}E_\Omega(r-\Lambda) + E_\Omega(r-2\Lambda)}{2}$$

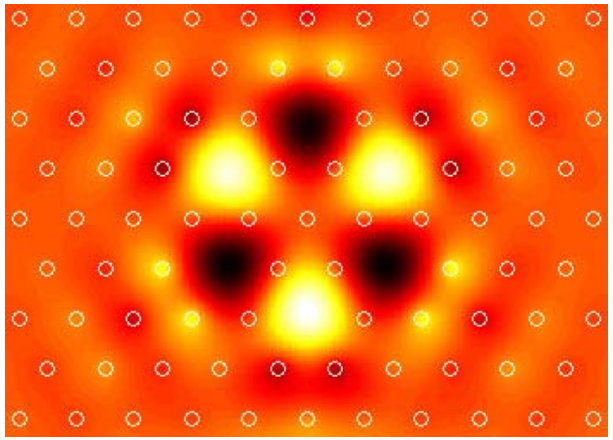






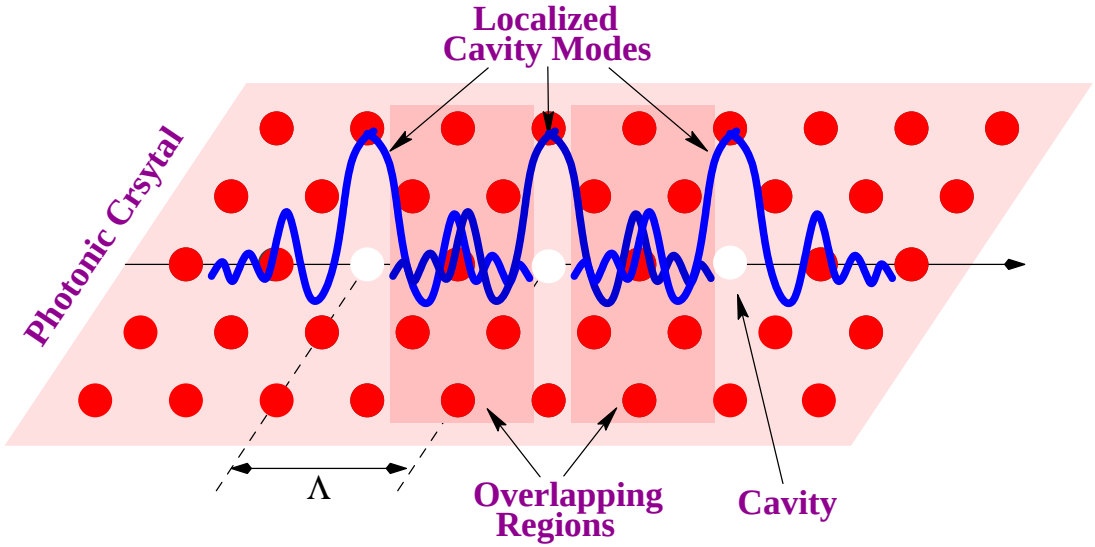






Benzene-like molecule

THE TIGHT-BINDING PICTURE IN PHOTONIC STRUCTURES



$$\nabla \times \left[\nabla \times \mathbf{E}(\mathbf{r})\right] = (\omega/c)^2 \varepsilon_0(\mathbf{r})\mathbf{E}(\mathbf{r})$$

$$\mathbf{E}(\mathbf{r}) = E_0 \sum_n e^{-ink\Lambda} \mathbf{E}_\Omega(\mathbf{r} - n\Lambda)$$

$$\omega(k) = \Omega\left(1 + \kappa \cos(k\Lambda)\right)$$

$$v_g(k) = \nabla_k \omega(k) = -\Omega\Lambda\kappa \sin(k\Lambda)$$

$$\tau_p(k) = L/v_g(k) - 2\pi L/c$$

✓ highly localized

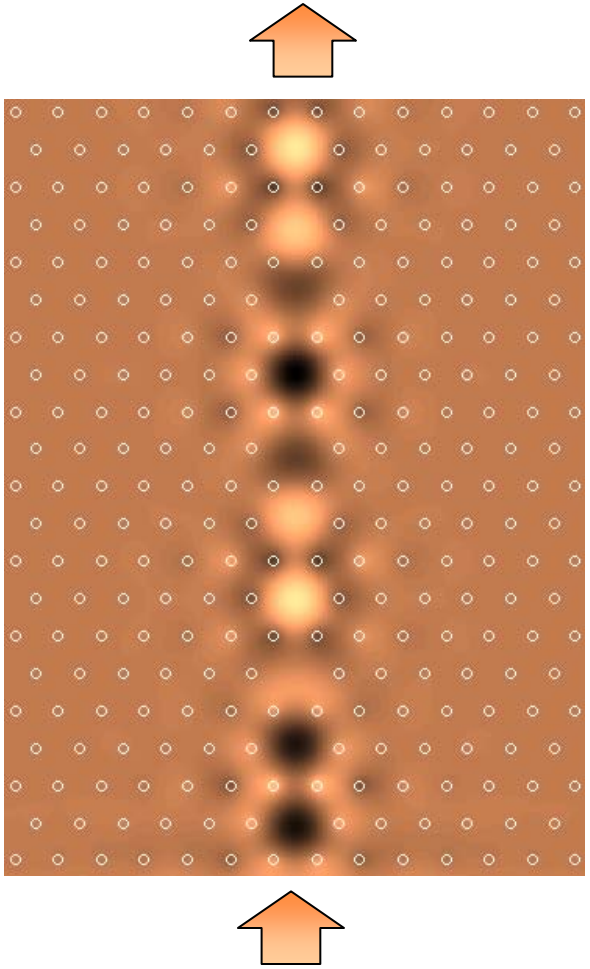
✓ weakly interacting cavity modes

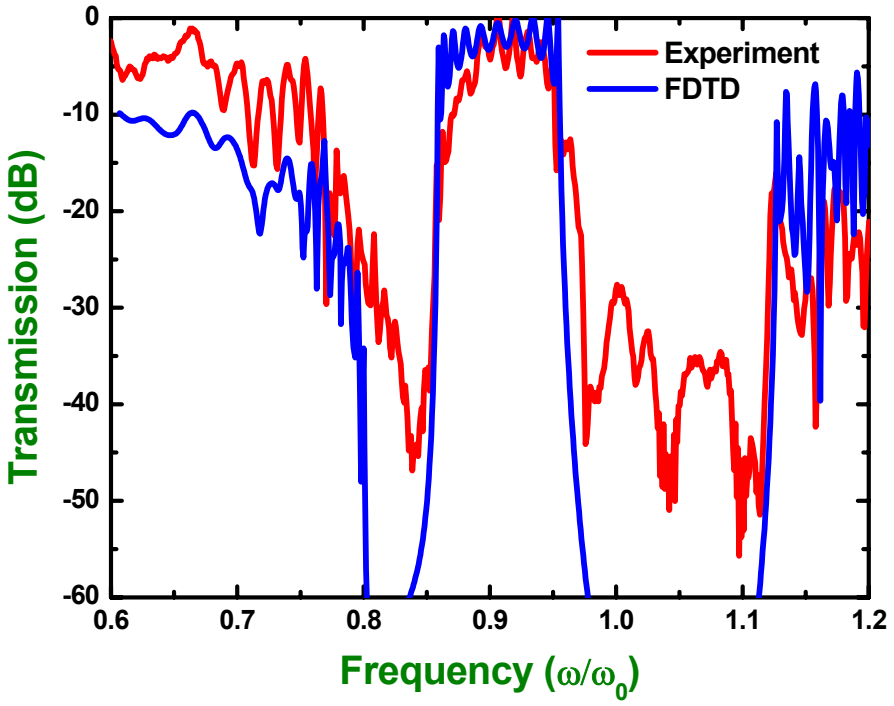
Tight-binding approximation

Dispersion relation, group velocity, and photon lifetime depend only a single tight-binding parameter κ that can be directly determined from experiments

Stefanou and Modinos, Phys. Rev. B **57**, 12127 (1998); Yariv *et al.*, Opt. Lett. **24**, 711 (1999)
Bayindir, *et al.*, Phys. Rev. Lett. **82**, 2140 (2000)

PROPAGATION OF PHOTONS BY HOPPING

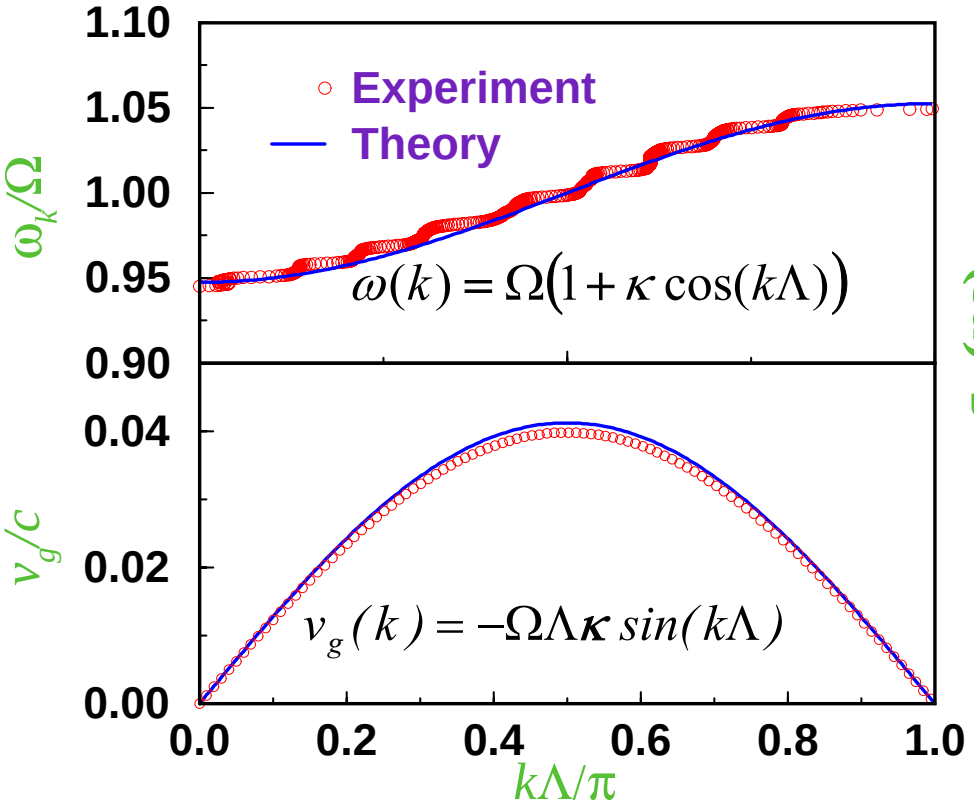


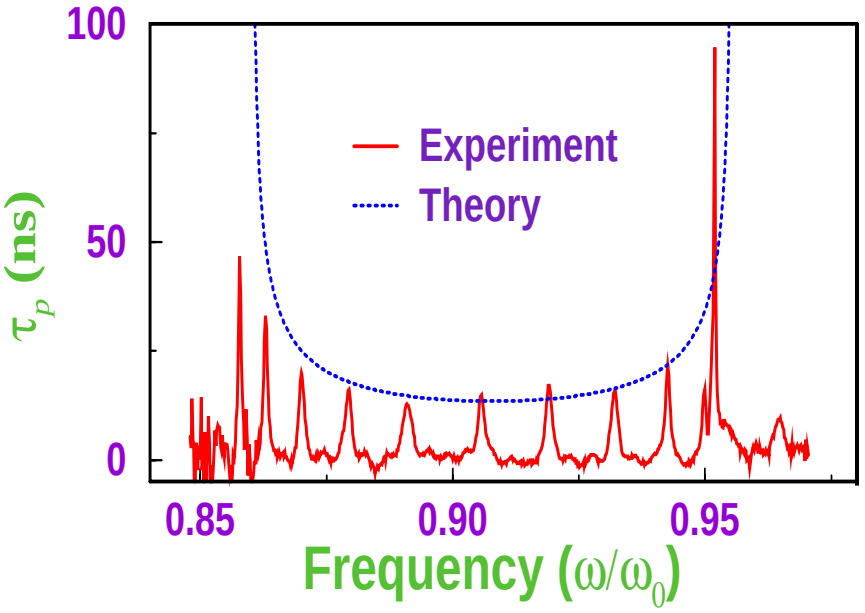


- Formation of a cavity band (waveguiding band) due to interaction between the localized modes
- Demonstration of a new type of waveguiding mechanism in photonic crystals.
  - Full transmission is measured throughout the CCW band
  - Very sharp band edges can be used for switching applications

Bayindir, *et al.*, Phys. Rev. B **61**, R11855 (2000); JQE (in press, 2002)

DISPERSION RELATION, GROUP VELOCITY, PHOTON LIFETIME: MEASUREMENTS AND CALCULATIONS





$$\tau_p(k) = L/v_g(k) - 2\pi L/c$$

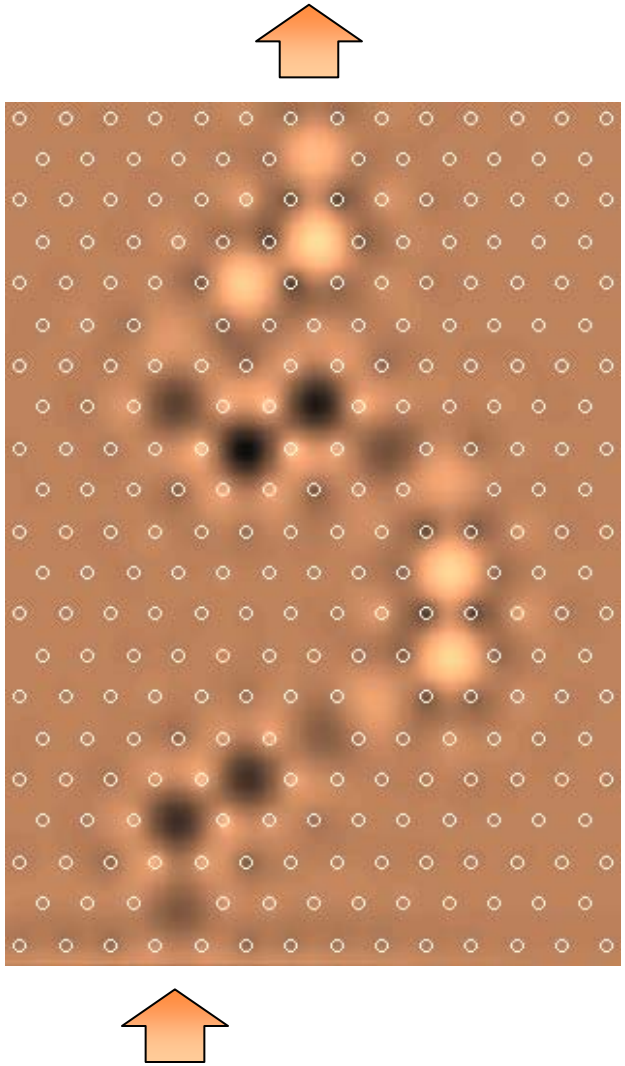
$v_g \to 0$

$\tau_p \to \infty$

at the CCW band edges ➡ **"heavy photon"**

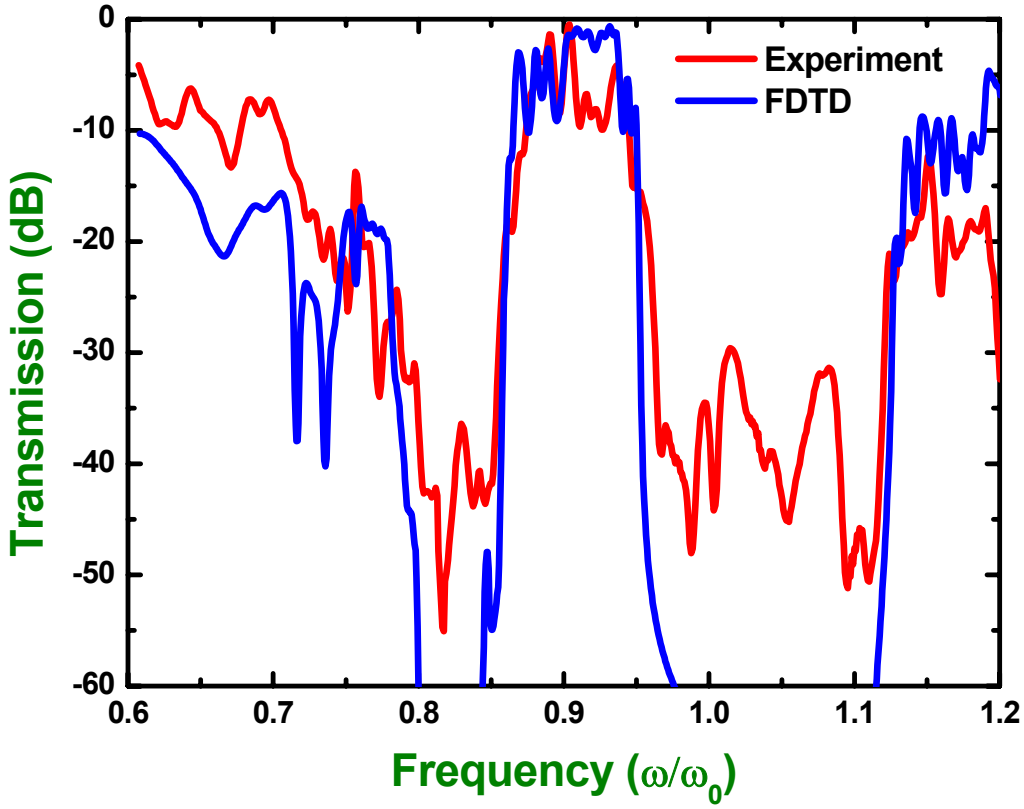
Bayindir and Ozbay, Phys. Rev. B **62**, R2247 (2000)

BENDING OF EM WAVES ALONG ARBITRARY PATH



Zig-zag Waveguide

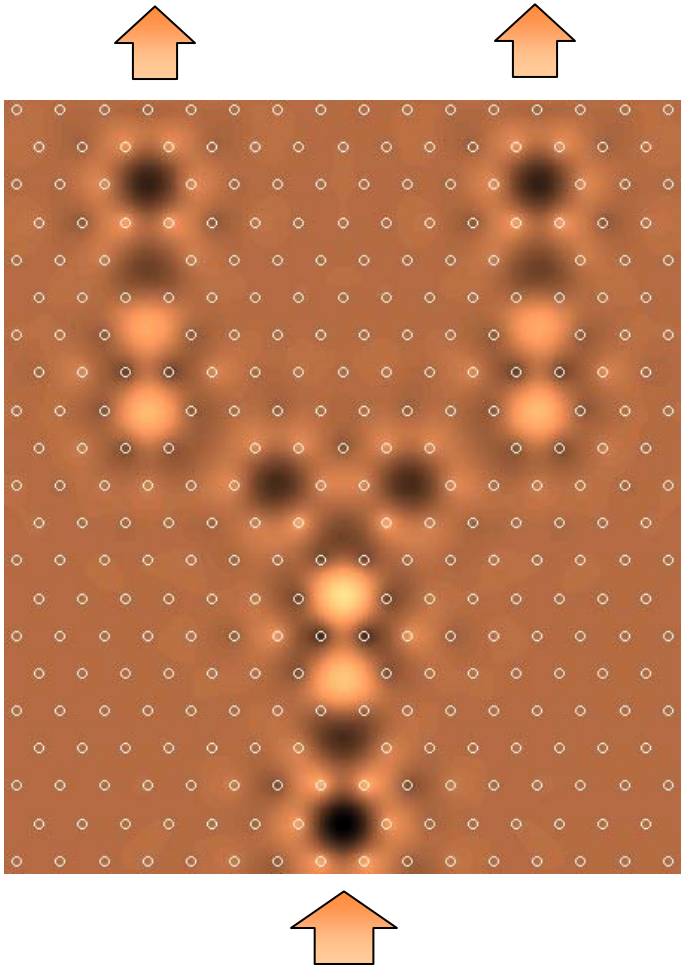
Problem of guiding light
around very sharp corners
in conventional waveguides

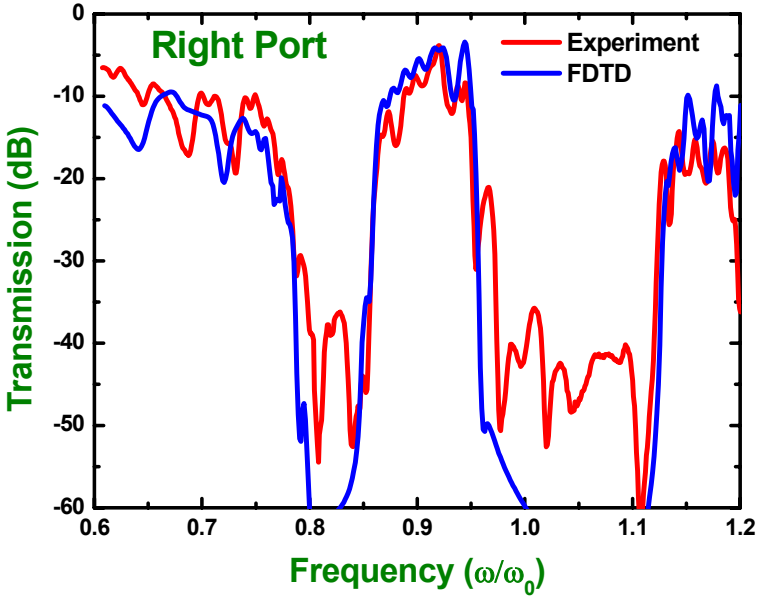


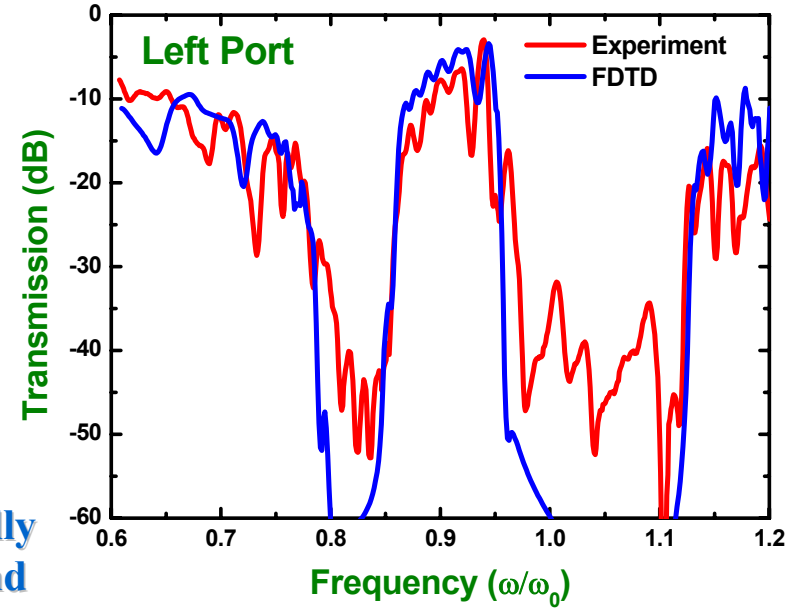
➢Possibility of constructing lossless and reflectionless bends in optical circuits

Bayindir, *et al.*, Phys. Rev. B **61**, R11855 (2000)

POWER SPLITTERS



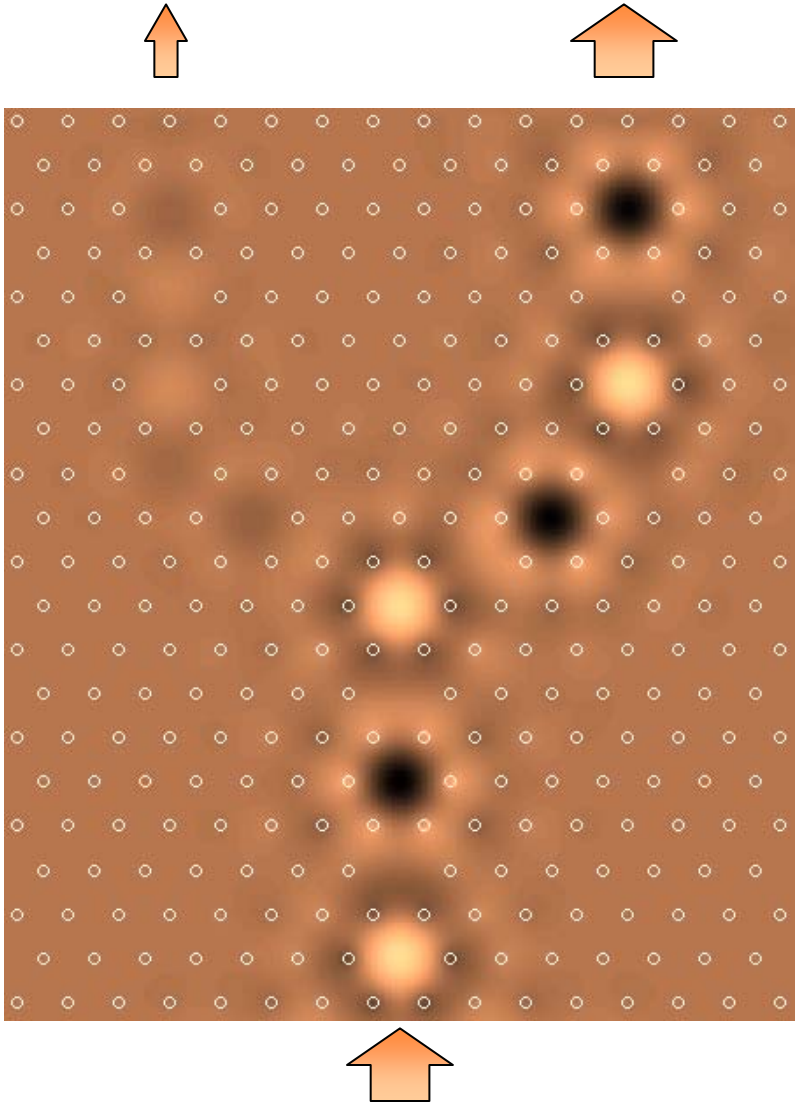


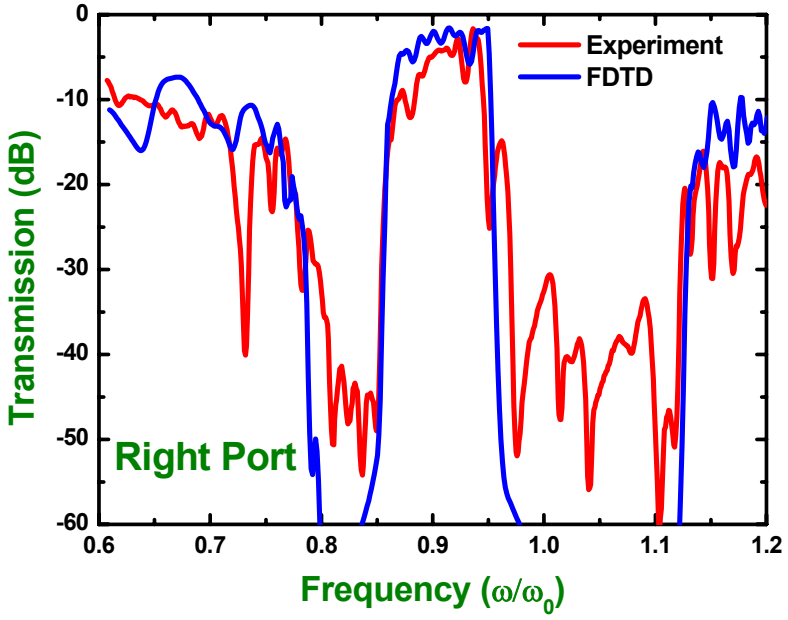


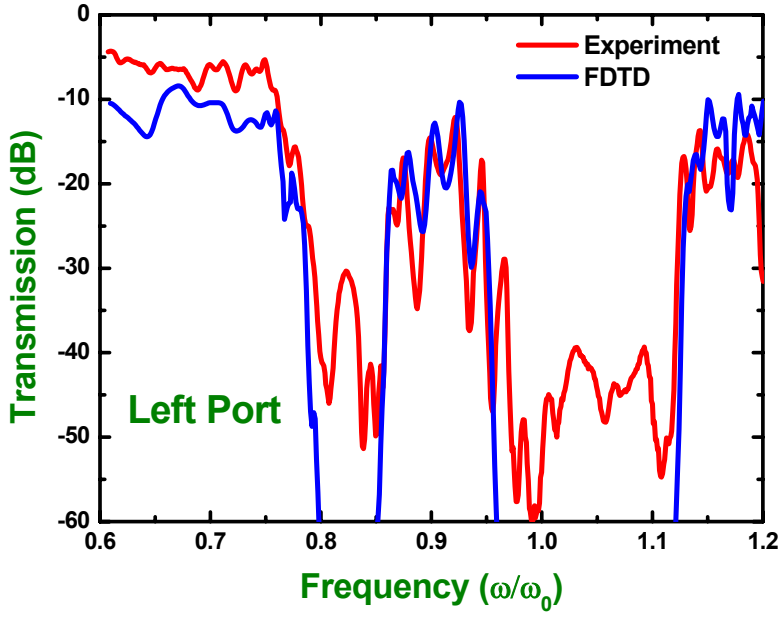
➢**The electromagnetic power in the input port splits equally into the two output ports throughout the waveguiding band**

Bayindir, *et al.*, Appl. Phys. Lett. **77**, 3902 (2000), JQE (in press)

COUPLED CAVITY SWITCHES

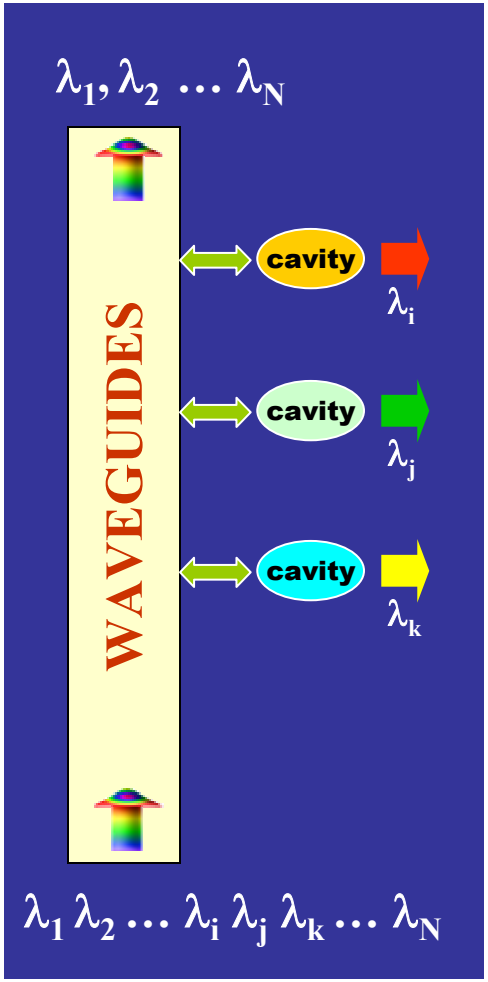




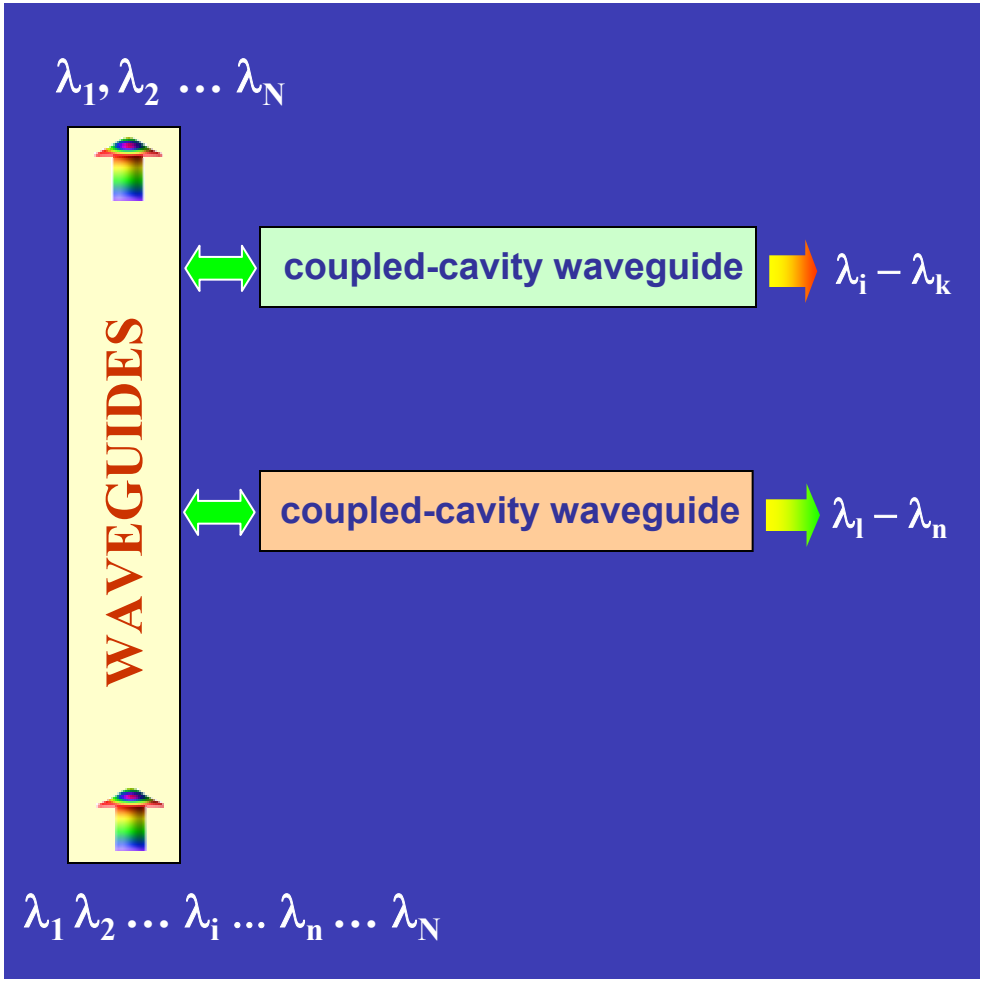


WDM APPLICATIONS

Single wavelength dropping

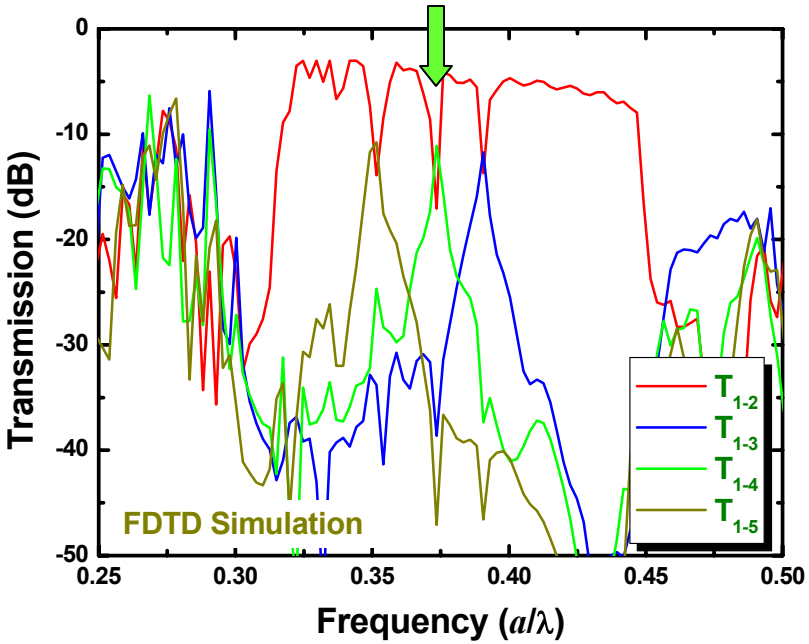


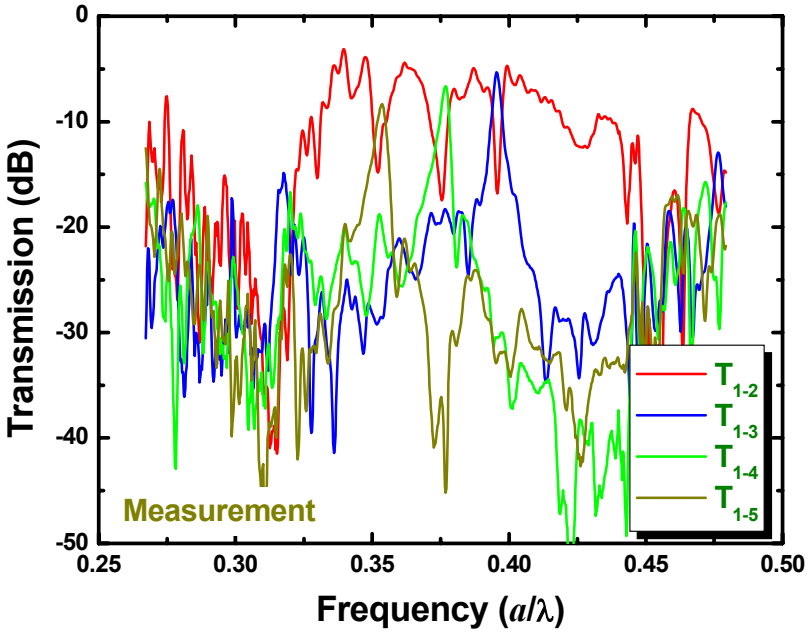
Band dropping

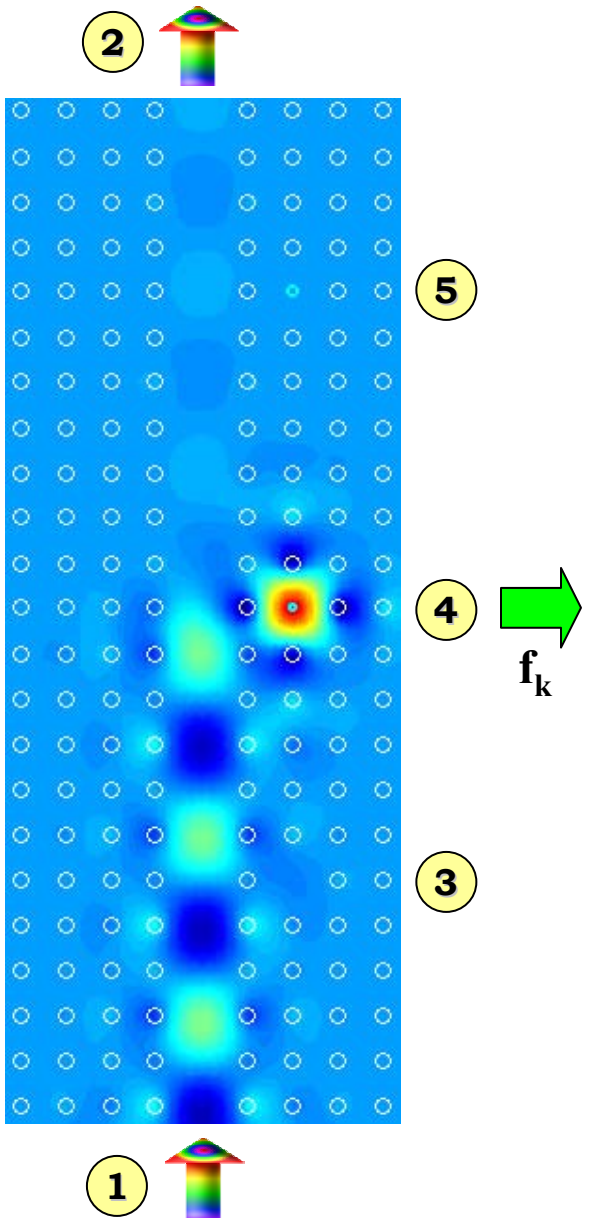


Bayindir and Ozbay, APL [submitted]

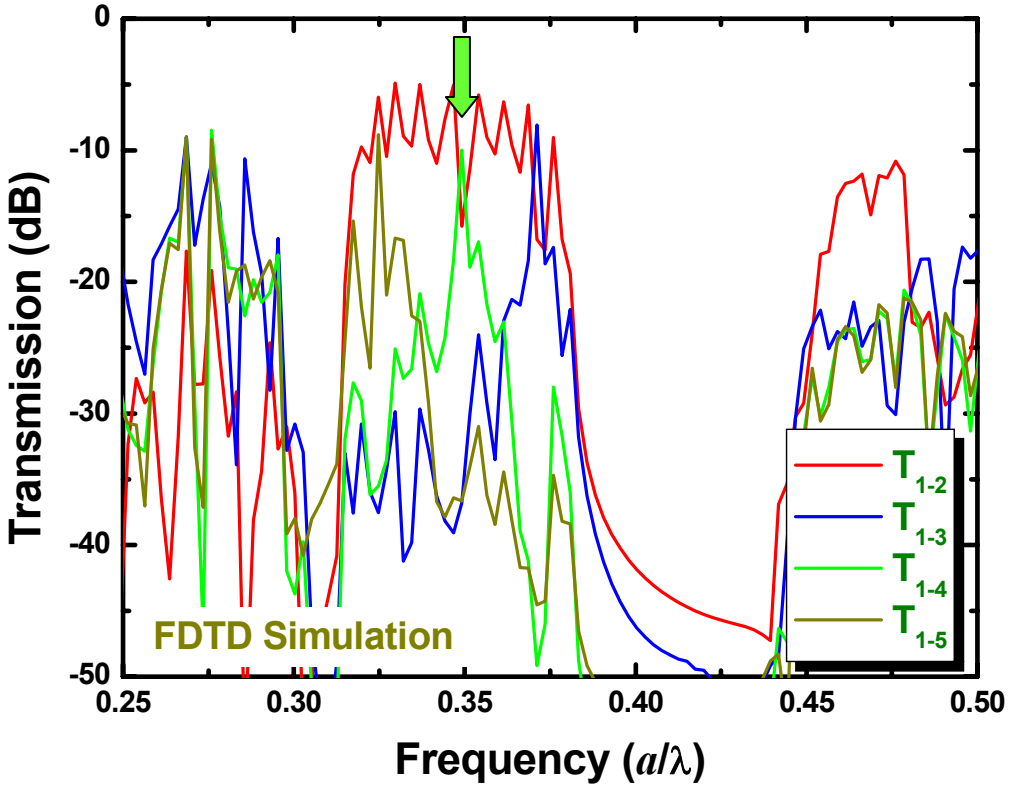
DROPPING OF A SELECTIVE FREQUENCY FROM PW

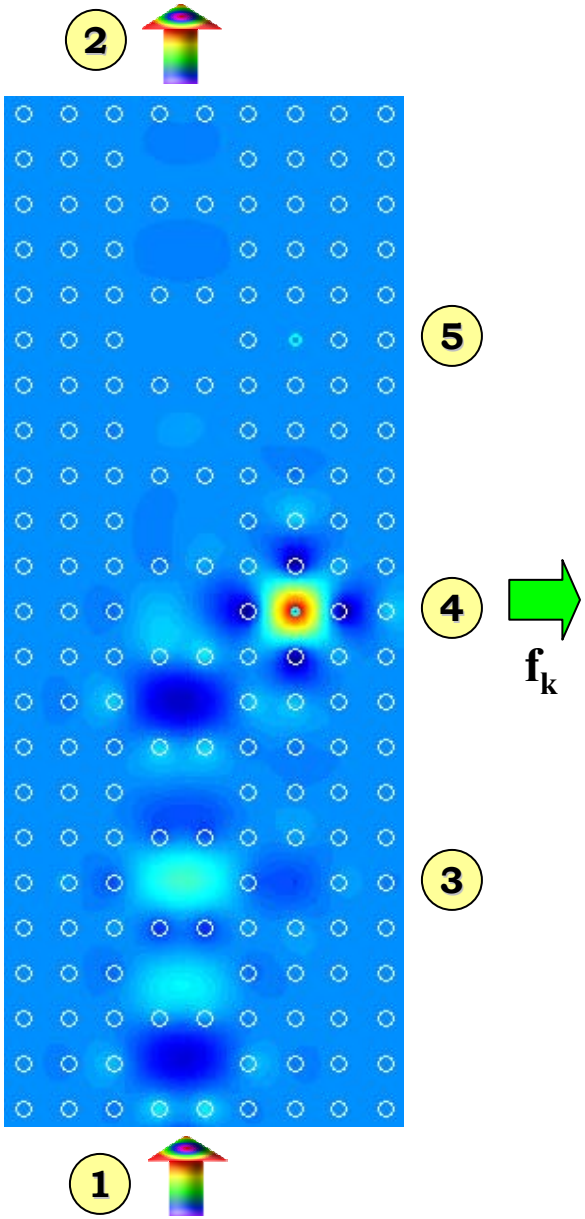




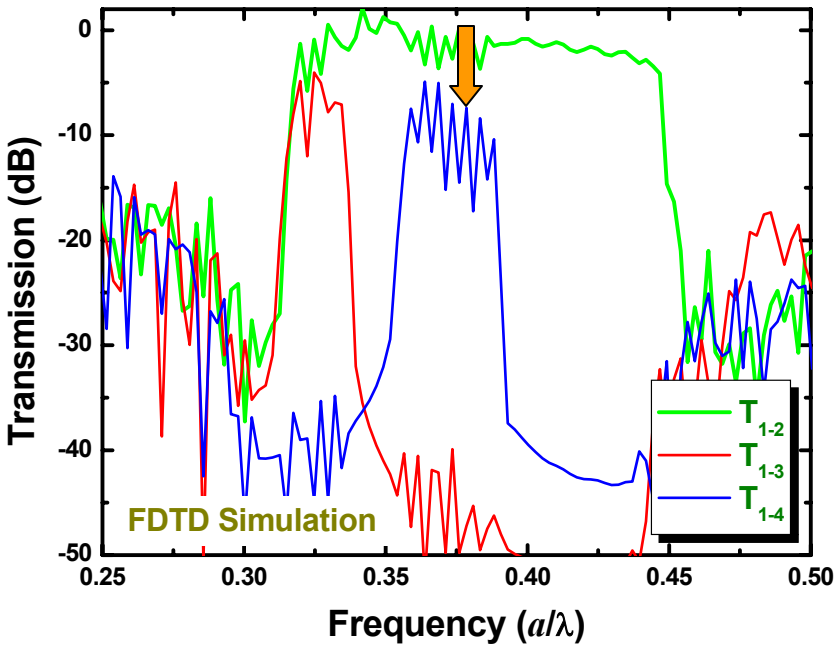


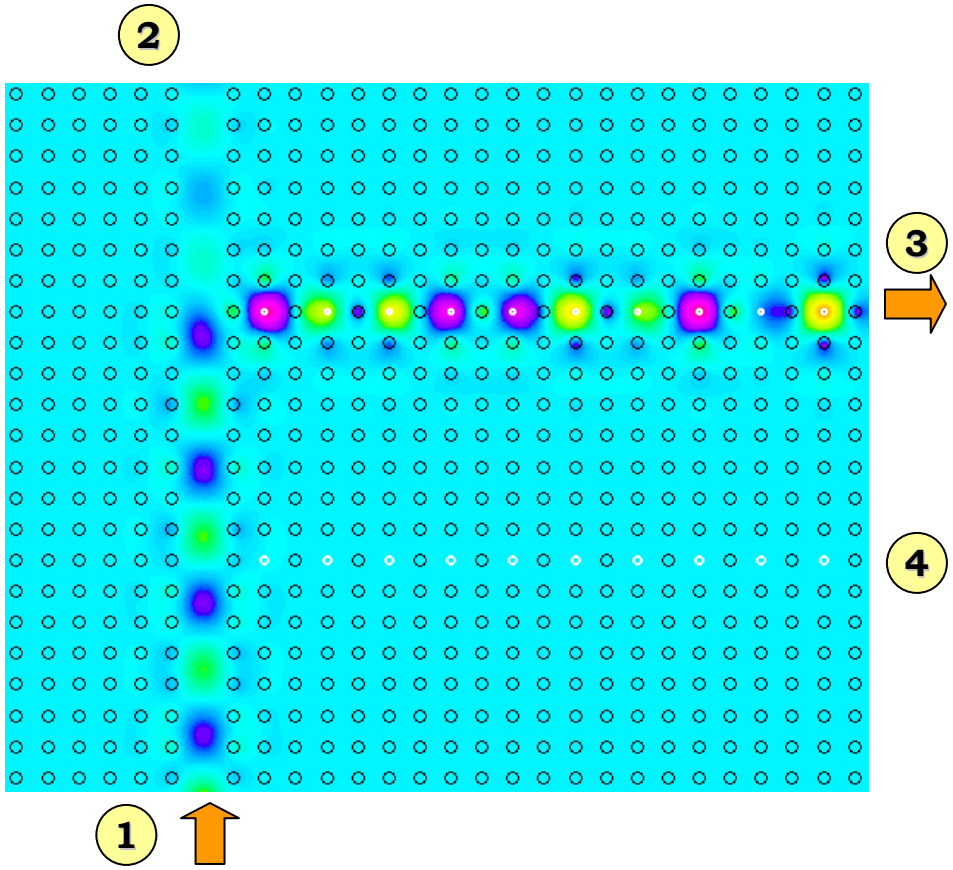
DROPPING OF A SELECTIVE FREQUENCY FROM CCW



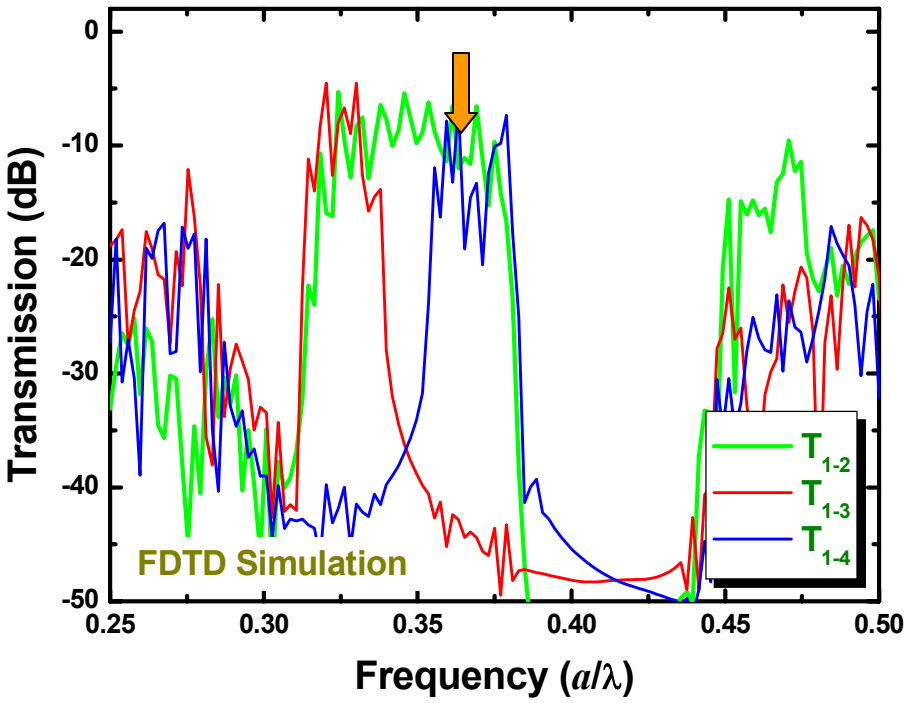


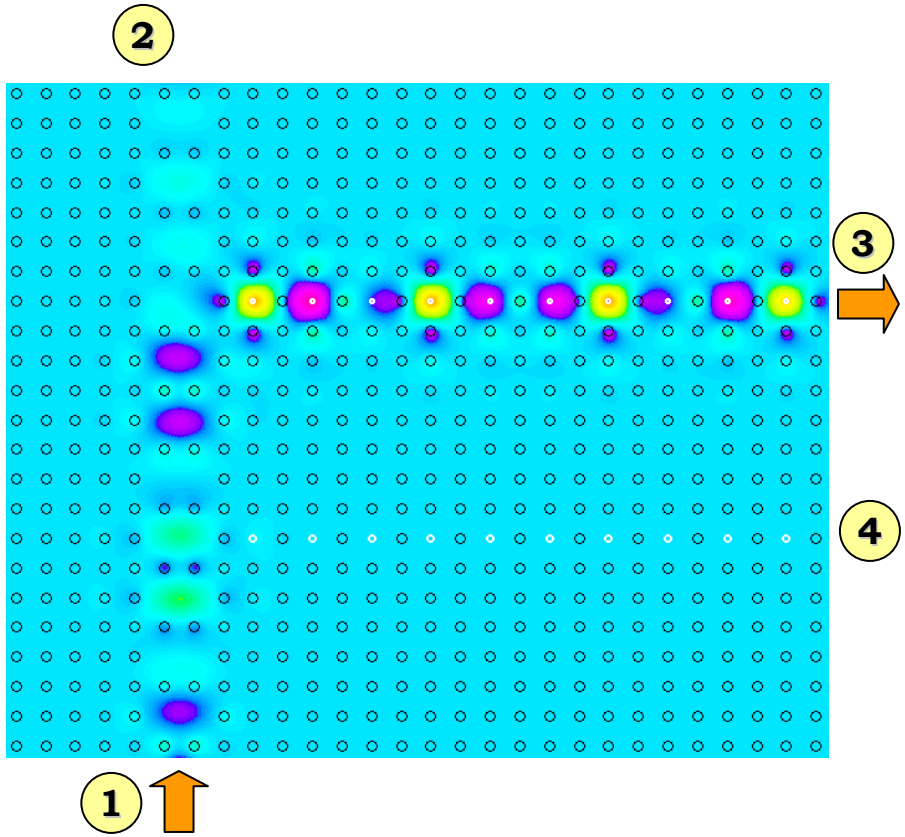
BAND DROPPING FROM PW



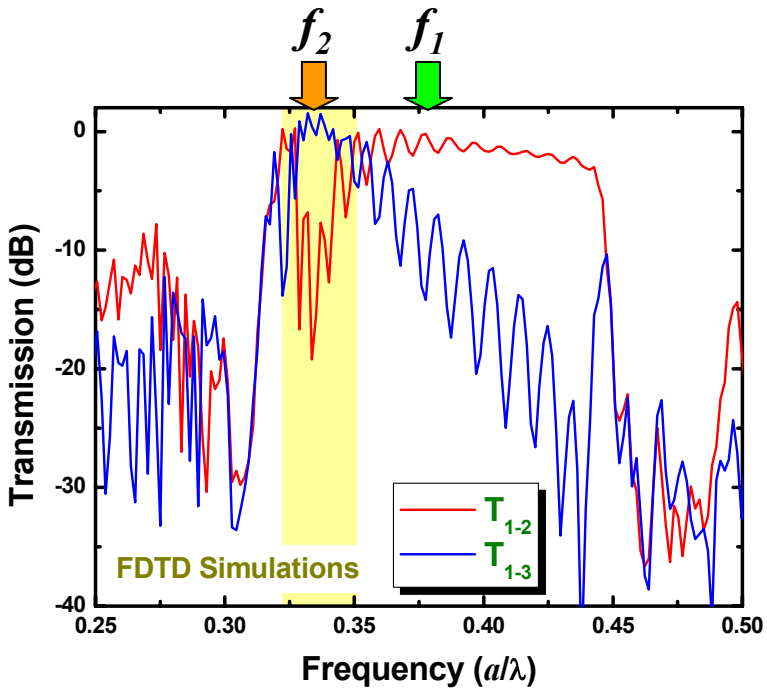


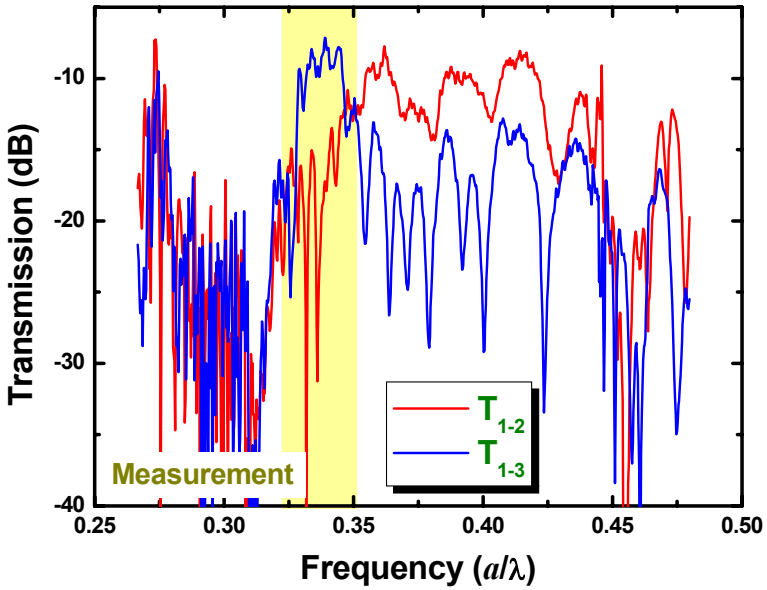
BAND DROPPING FROM CCW

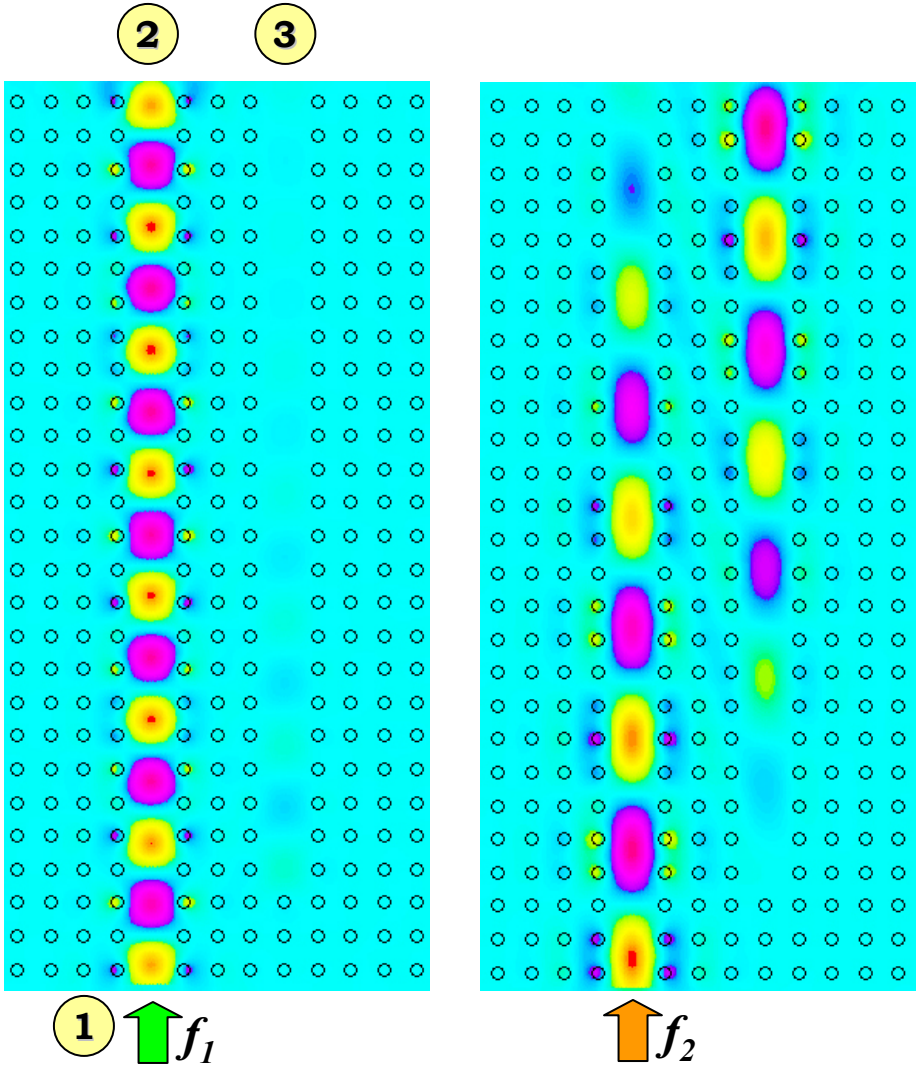




COUPLED WAVEGUIDES: DIRECTIONAL COUPLERS

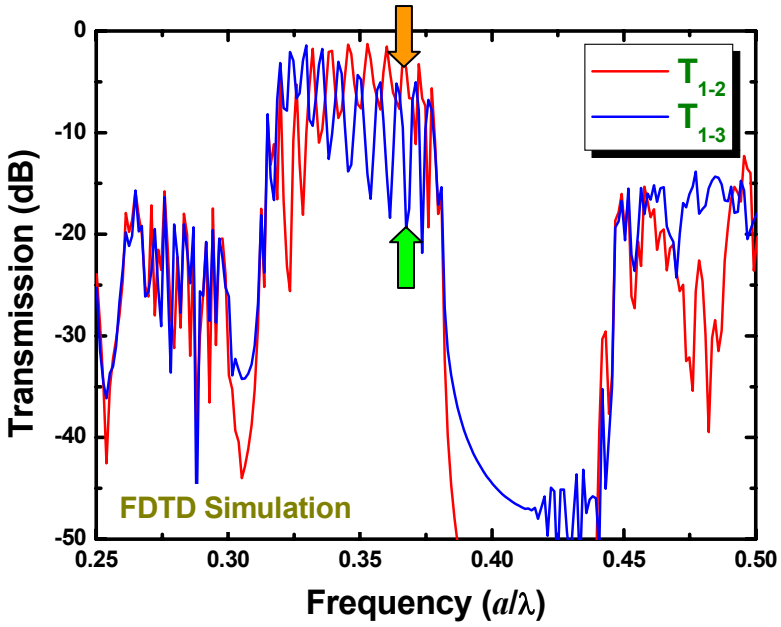


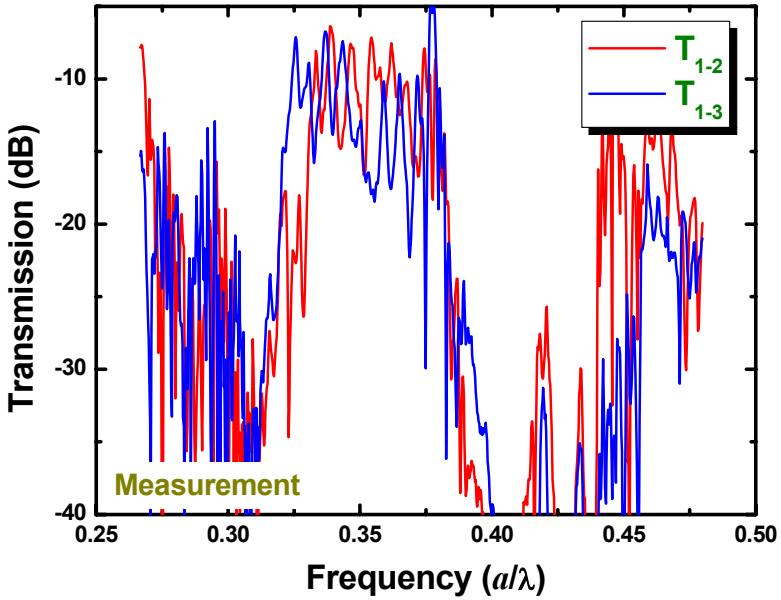


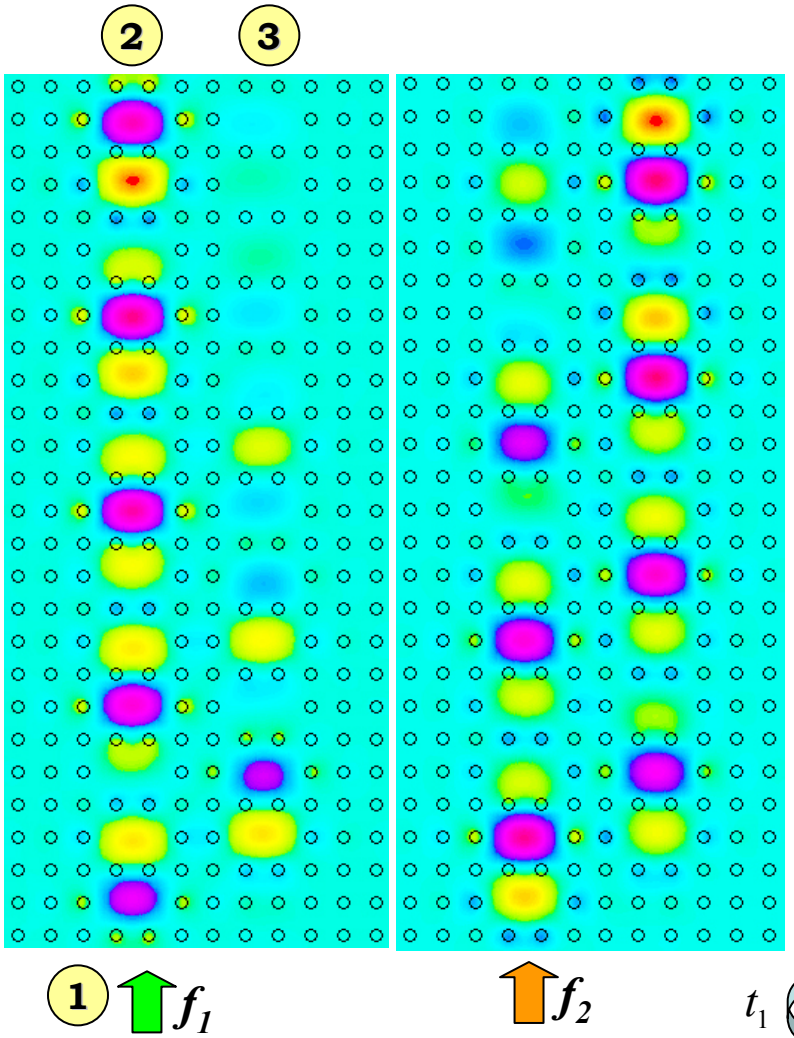


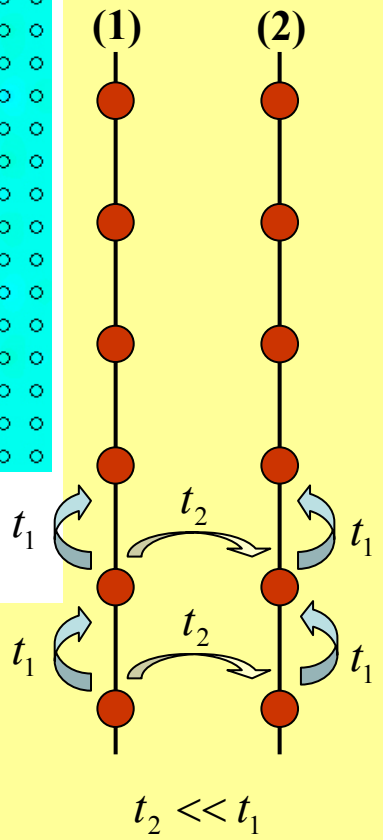
Bayindir and Ozbay, Optics Express [in preparation]

DIRECTIONAL COUPLERS: COUPLED-CAVITY WAVEGUIDES









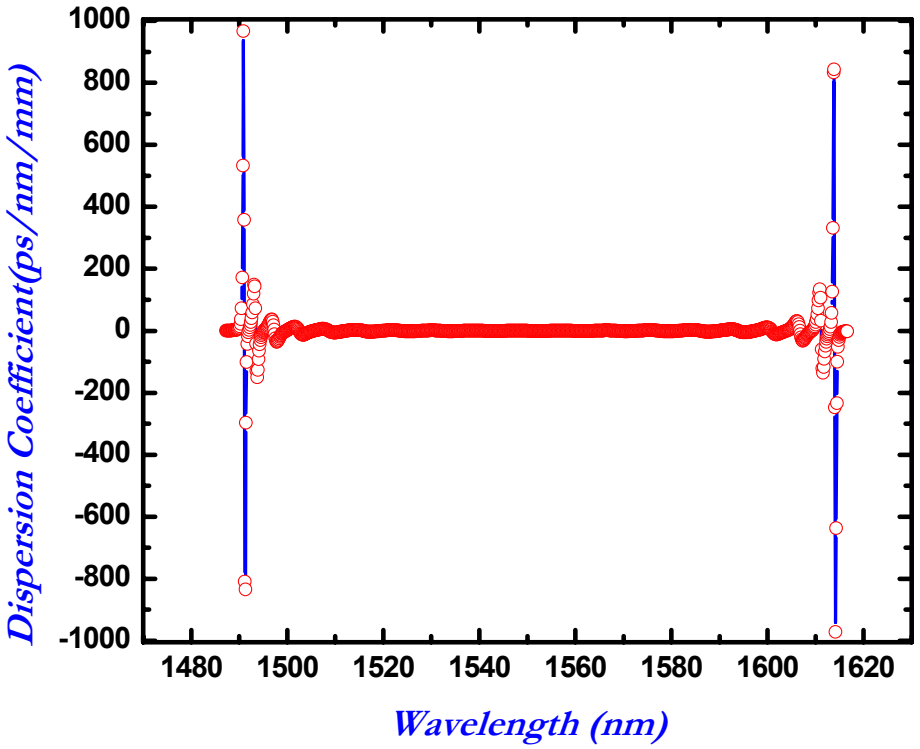
TIGHT-BINDING MODEL: INTERACTING CHAINS

INCREASING EFFICIENCY OF NONLINEAR PROCESESS

$$\eta \propto 1/v_g \qquad v_g \to 0$$

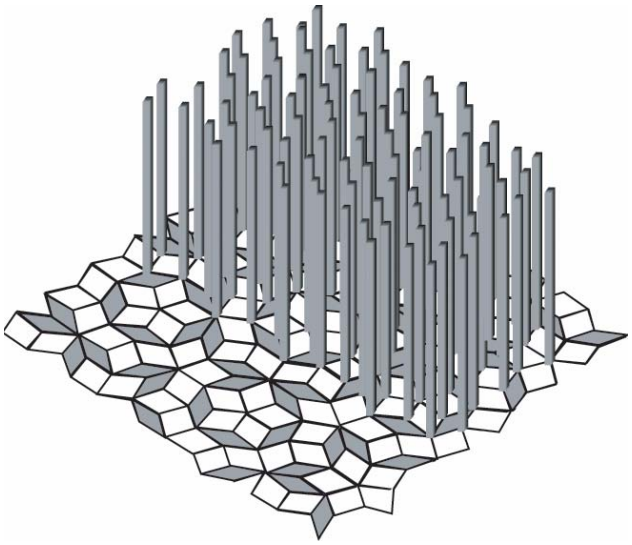
Large gain

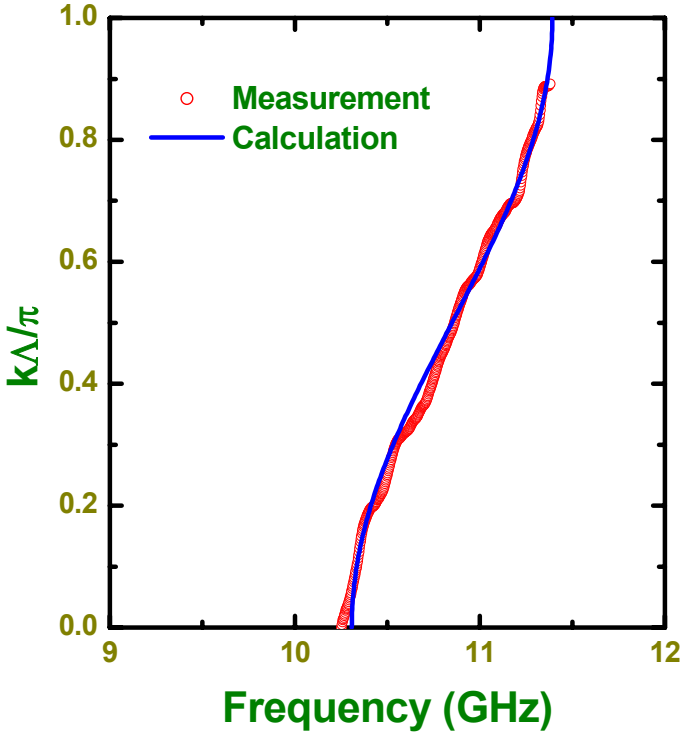
DISPERSION COMPENSATORS

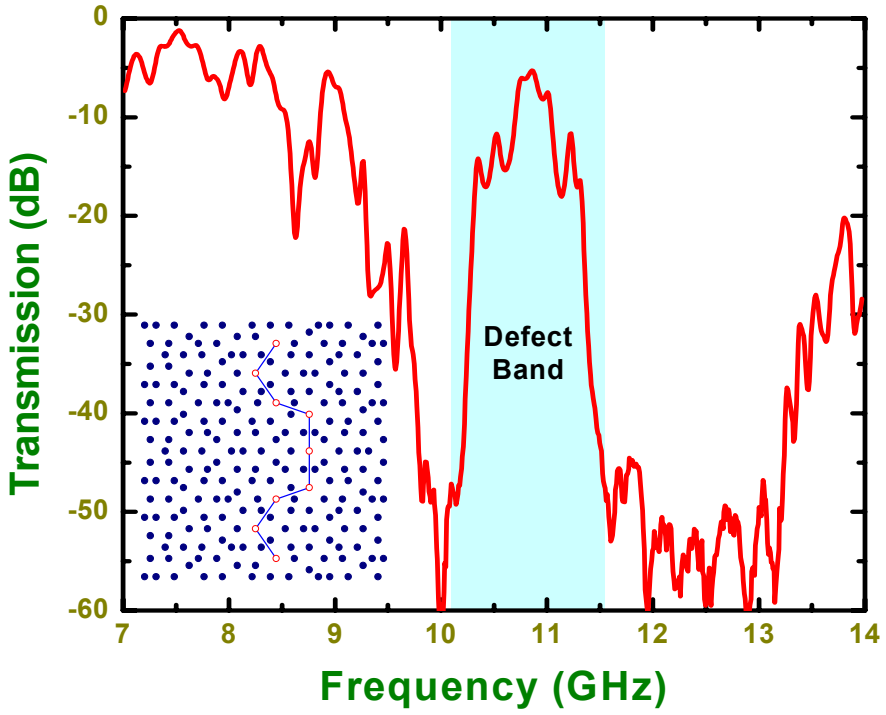


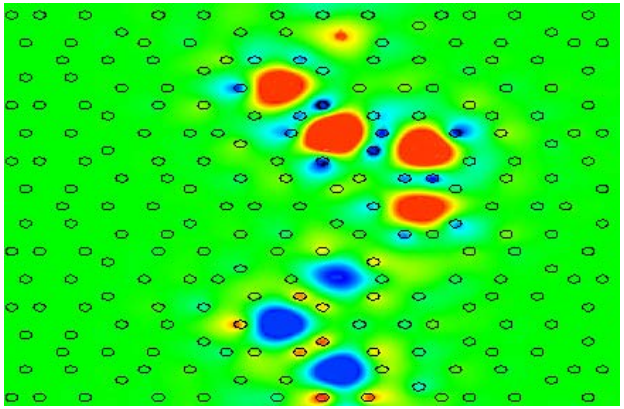
$$D = -\frac{2\pi c}{\lambda^2}\frac{d^2k}{d\omega^2}$$

QUASIPERIODIC [PENROSE] PHOTONIC CRYSTALS



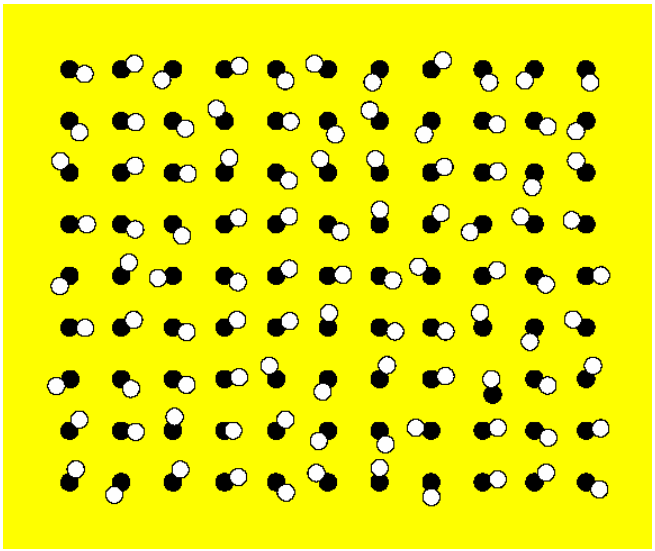






COUPLED-CAVITIES IN DISORDERED CRYSTALS

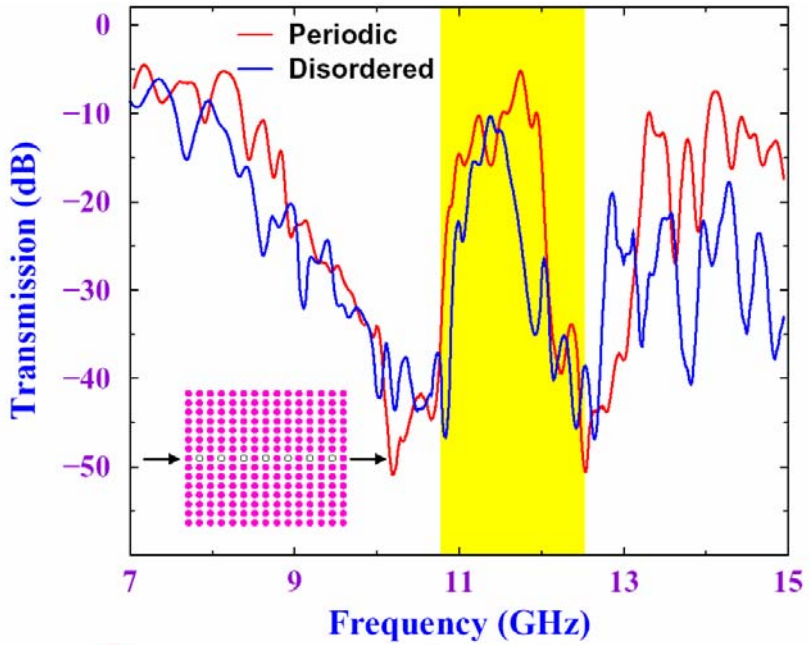
● periodic photonic crystal
○ disordered photonic crystal

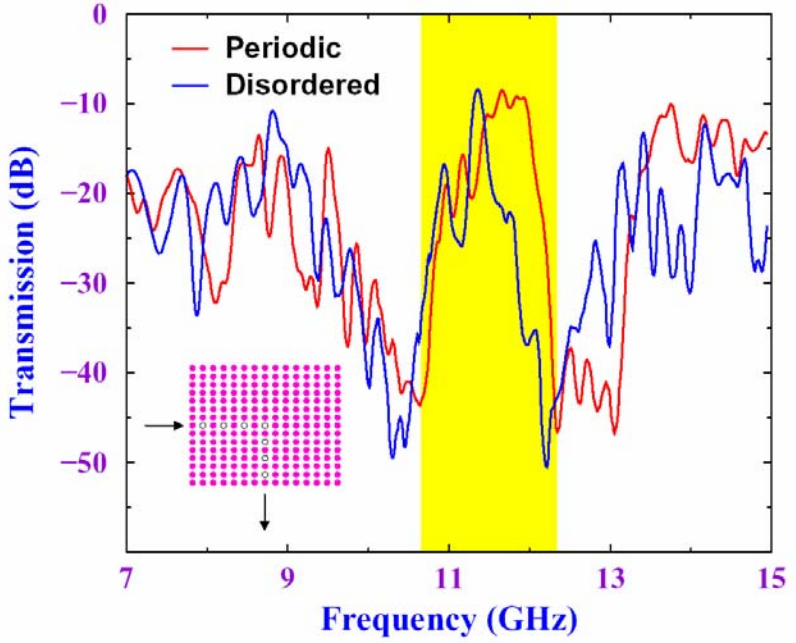


$$z_i \rightarrow z_i r e^{i\varphi}$$

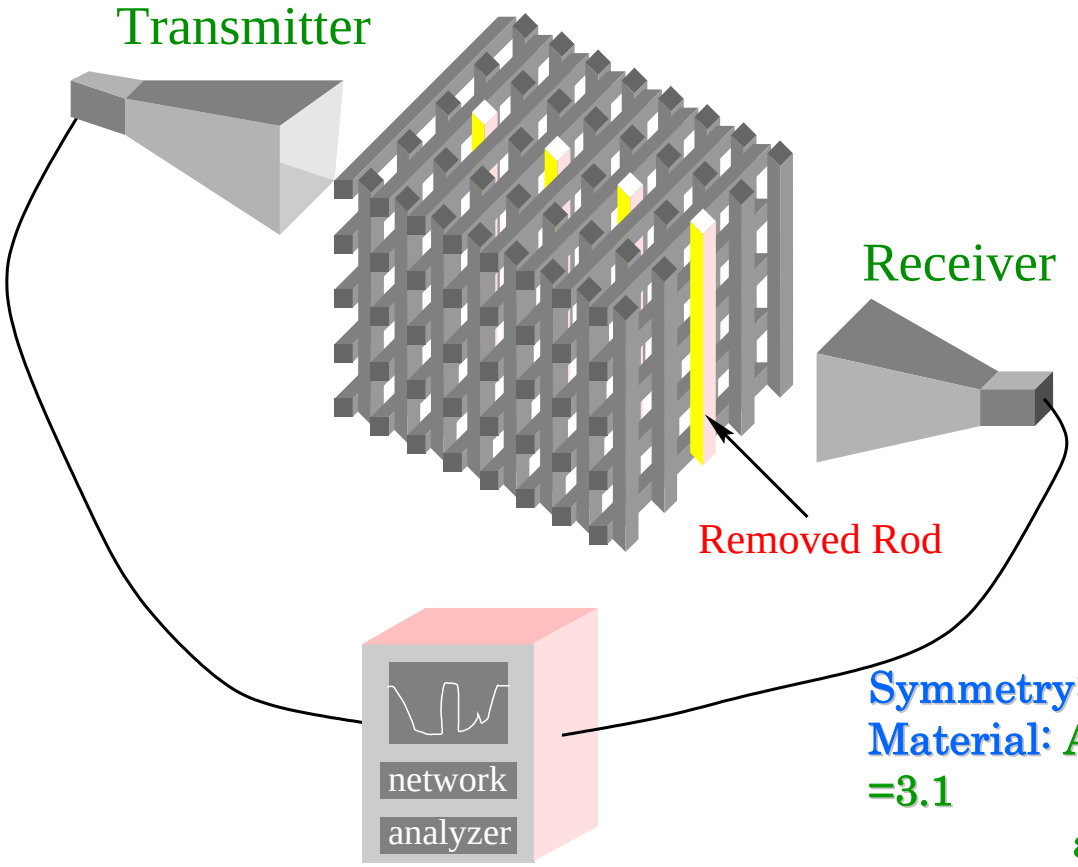
r : randomness parameter

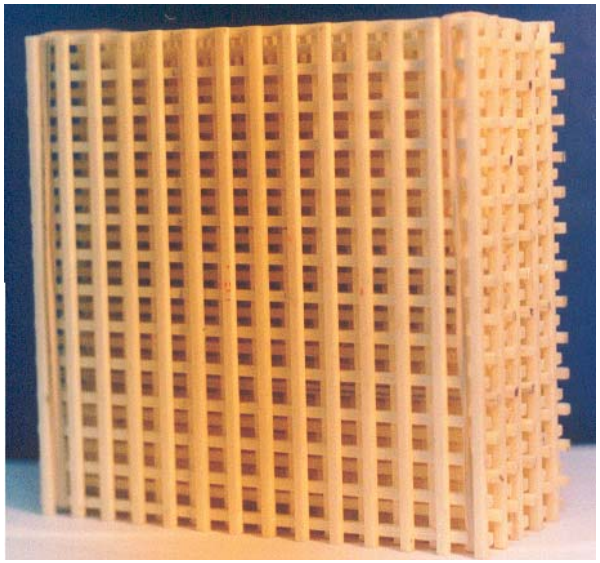
φ : random variable between $[0, \pi]$





3D LAYER-BY-LAYER PHOTONIC CRYSTALS



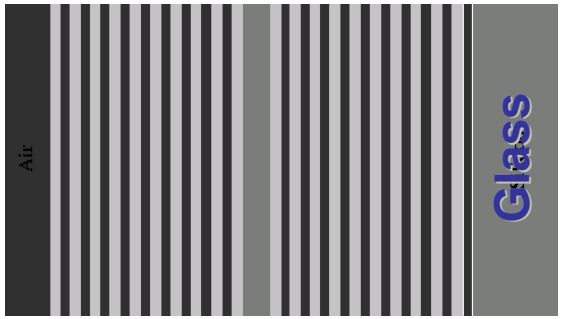


Symmetry: Face centered tetragonal (fct)
Material: Alumina of refractive index $\varepsilon = 3.1$ at microwave frequencies
Dimensions: 0.32 cm × 0.32 cm × 15.25 cm
Three-dimensional stop band: from 10.6 GHz to 12.8 GHz

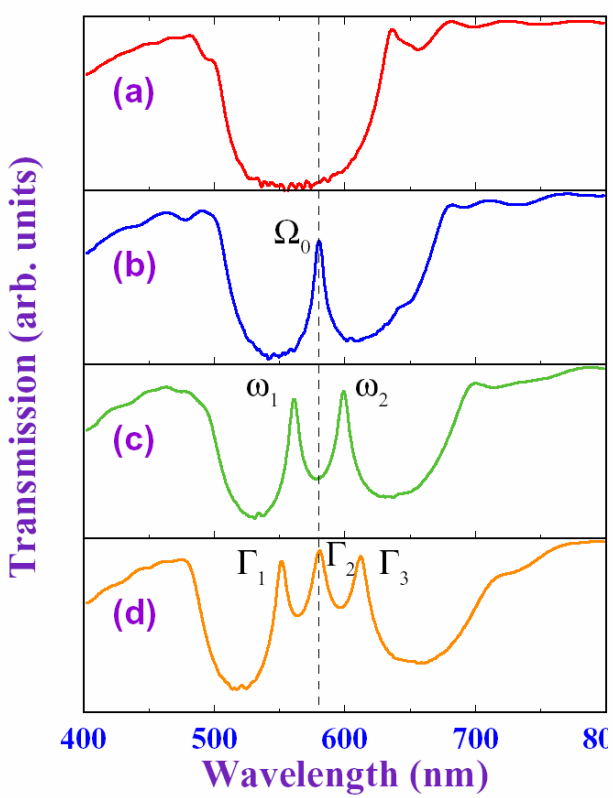
All phenomenon were observed in 3D layer-by-layer or woodpile structures

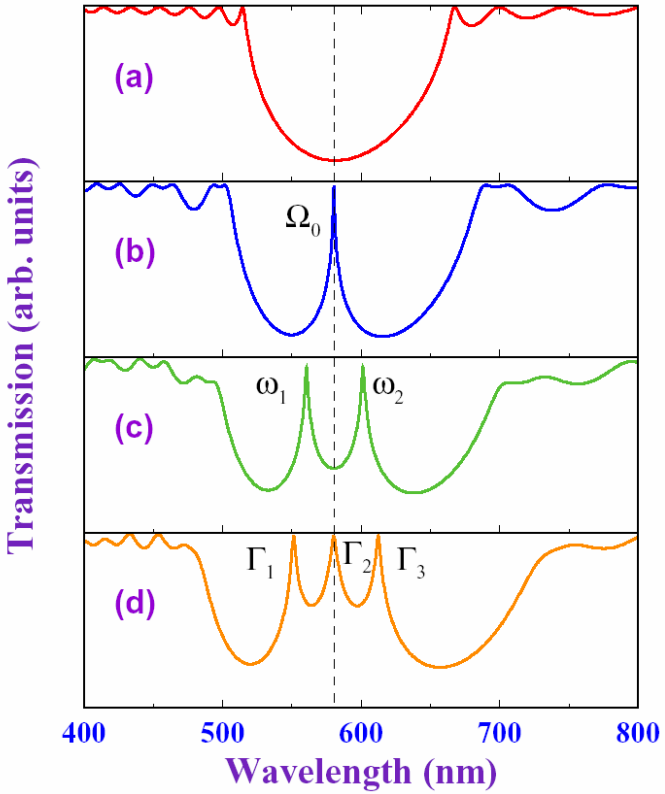
Bayindir, *et al.*, Phys. Rev. Lett. **82**, 2140 (2000); Bayindir, *et al.*, Phys. Rev. B **61**, R11855 (2000)

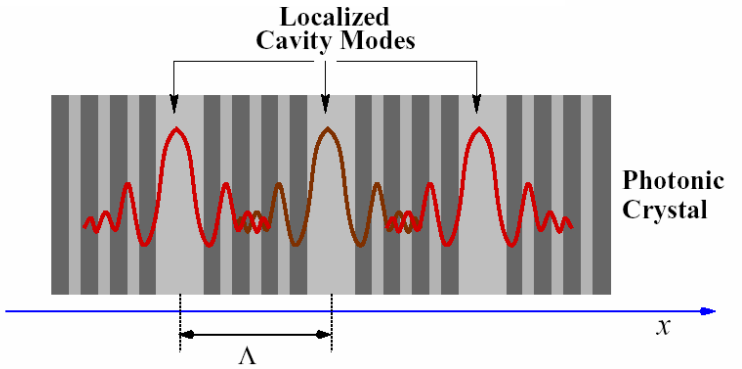
COUPLED-CAVITIES IN 1D STRUCTURES



	n	d [nm]
Si_3N_4	2.10	70
SiO_2	1.47	97





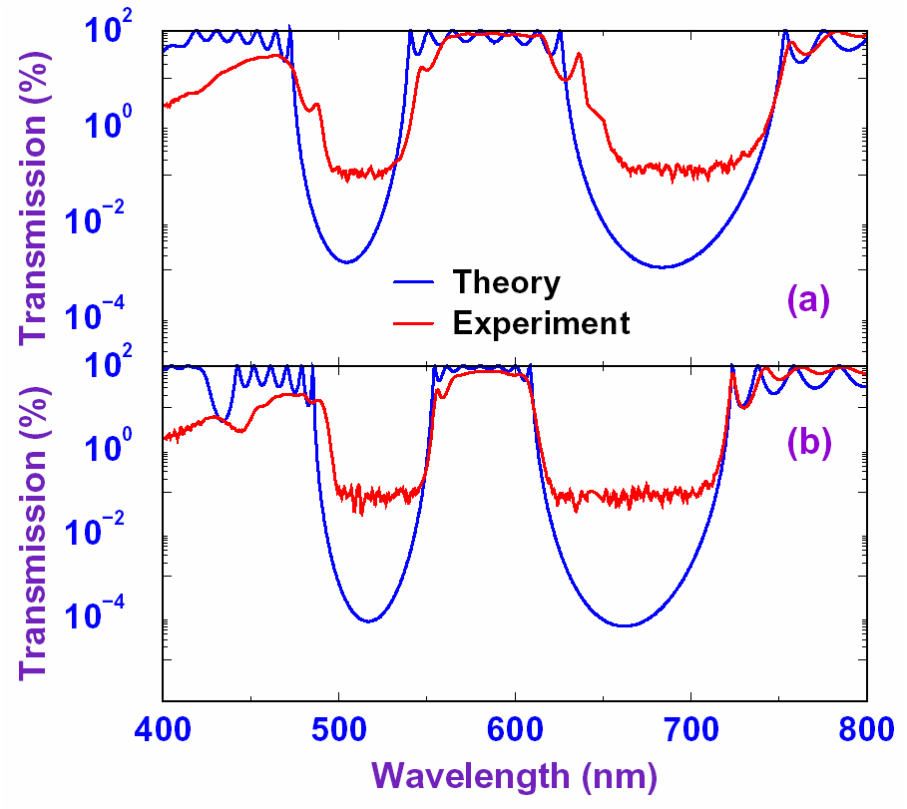


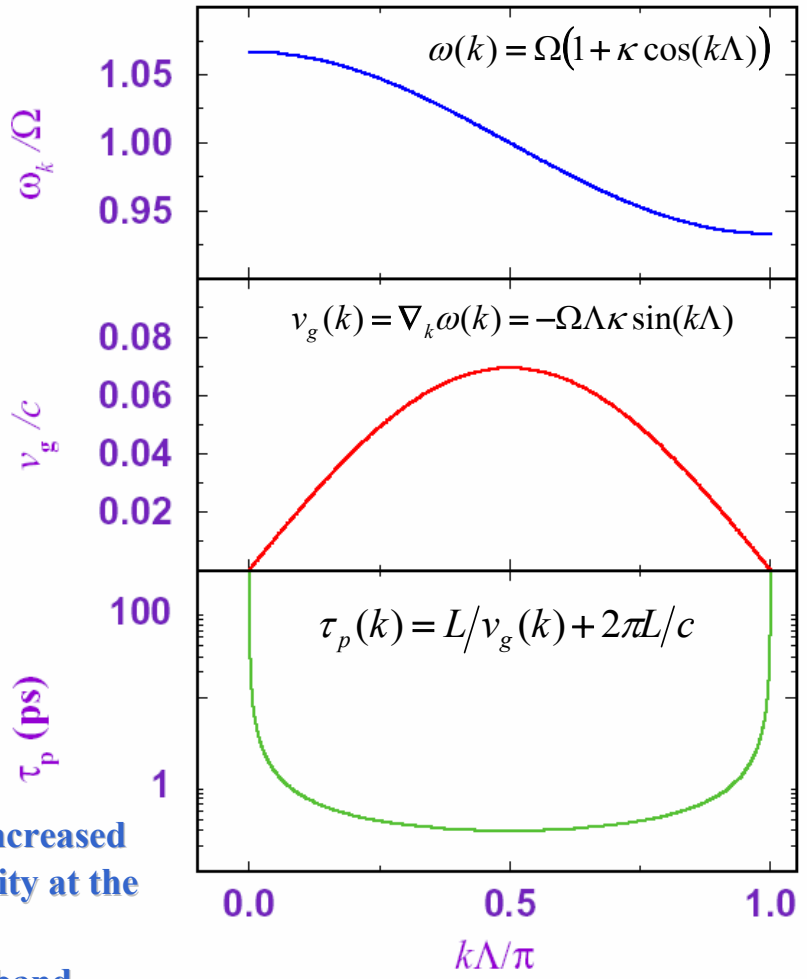
	Measurement [THz]	TMM [THz]	TB [THz]
Γ_1	490.08	491.30	489.85
Γ_2	516.53	516.80	516.83
Γ_3	543.65	542.81	544.10

Bayindir, *et al.*, Appl. Phys. A 72, 117 (2001); Appl. Phys. A 73, 125 (2001)

Experimental results agree well with TMM and TB predictions for the three coupled-cavities

COUPLED-CAVITIES IN 1D STRUCTURES



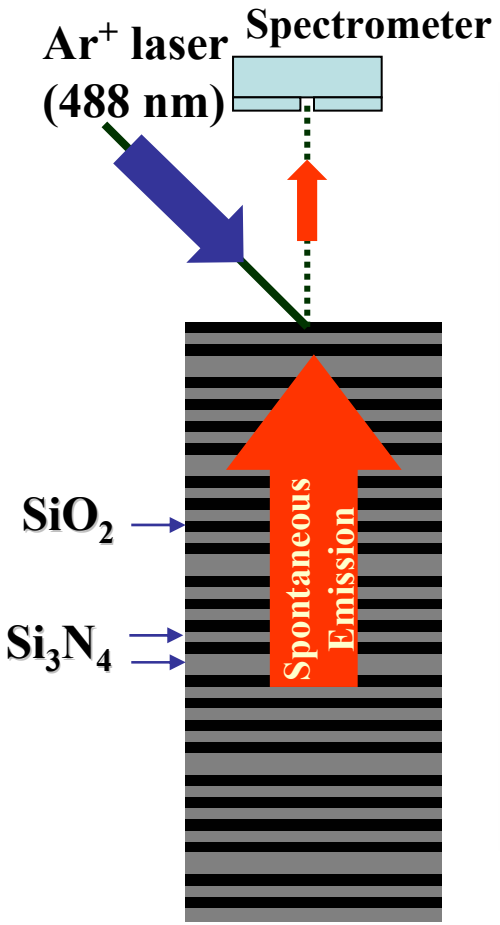


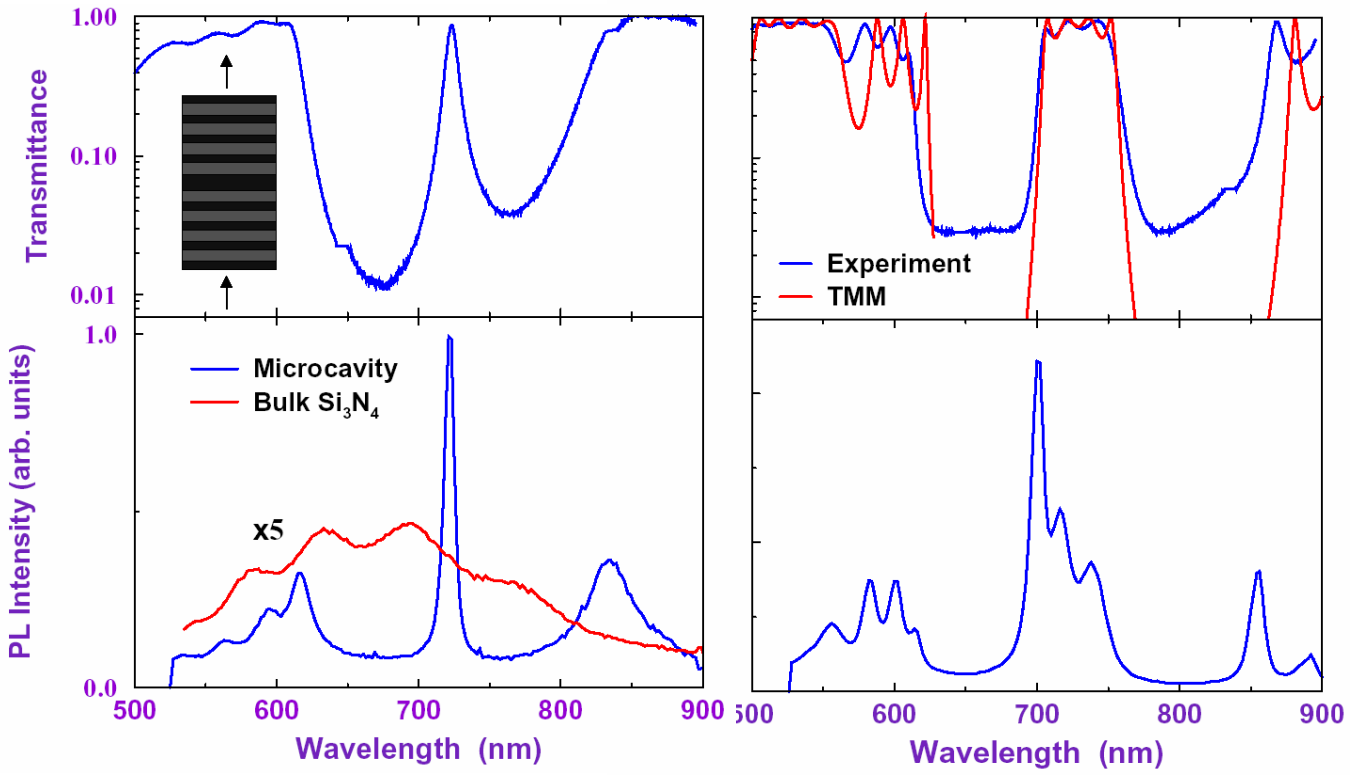
- Efficiency of the second harmonic generation process can be increased as a result of large optical field amplitude and low group velocity at the waveguiding band edges
- Nearly full transmission was measured throughout the CMC band
- The transfer matrix method results agree well with the experimental observations
- The position and bandwidth of waveguiding band can be adjusted by changing the thicknesses of the layers and the distance between the cavity layers

at the CMC band edges $v_g \rightarrow 0$, $\tau_p \rightarrow \infty$

heavy photon

PHOTOLUMINESCENCE FROM THE COUPLED-MICROCAVITY STRUCTURE

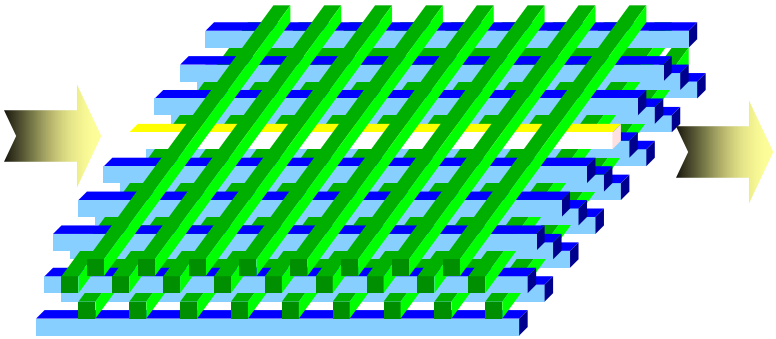




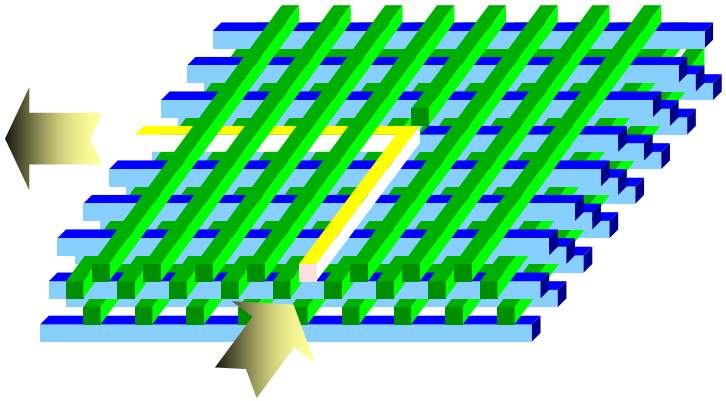
- The photoluminescence spectrum was strongly modified in the presence of Fabry-Perot microcavity
- A strong spontaneous emission was achieved for a wide range of wavelengths
- The spontaneous emission was significantly enhanced at the coupled-cavity band edges

HIGHLY CONFINED WAVEGUIDES

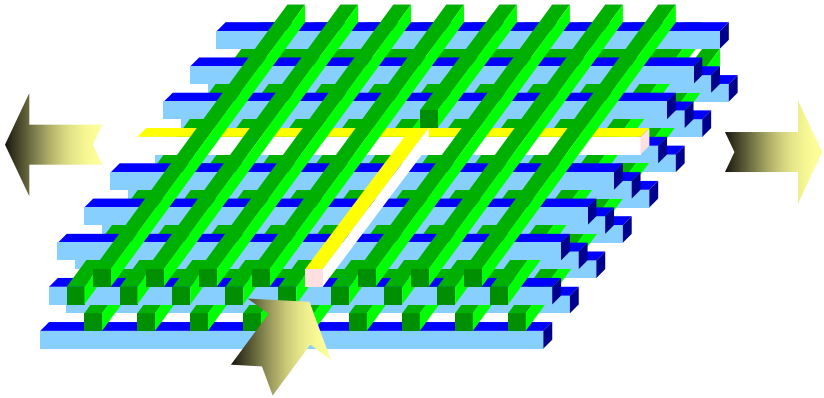
Straight Waveguide

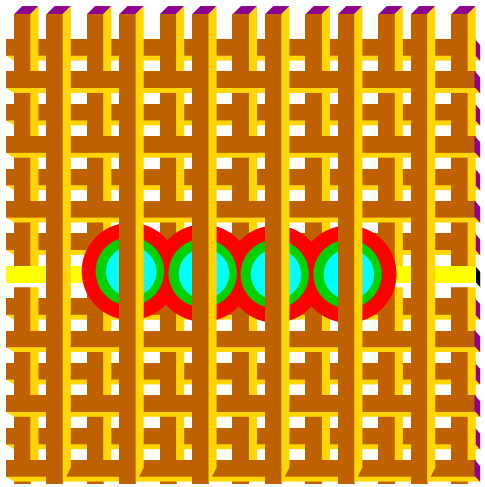


Bended Waveguide



Power Splitter

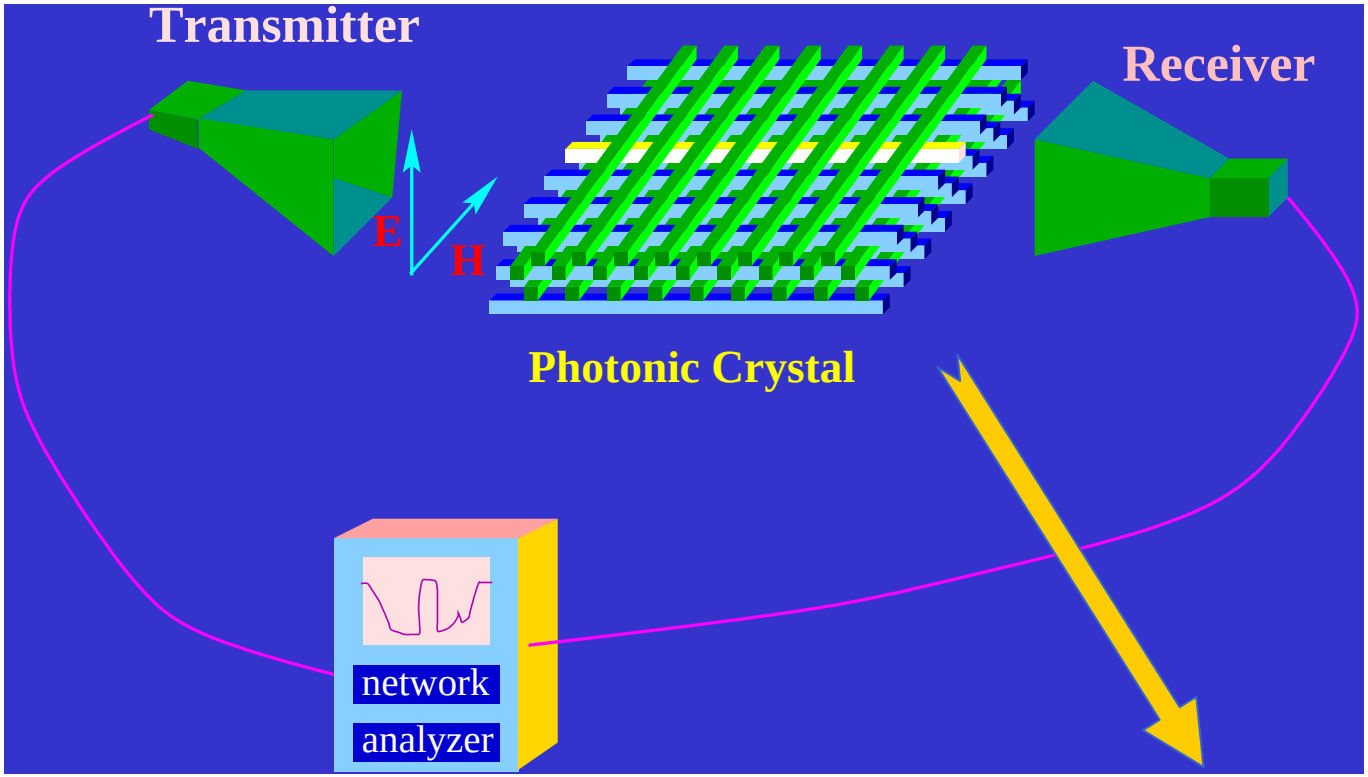




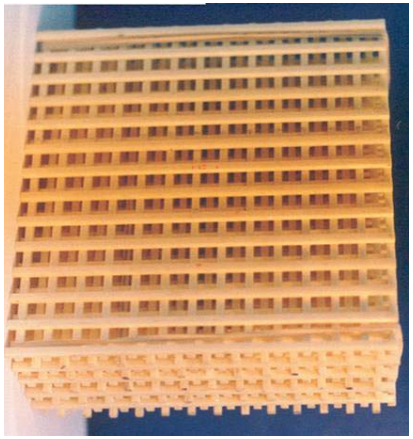
Noda *et al*, APL 75, 3739 1999;
Bayindir *et al.*, PRB 63, 081107(R) (2001)

Full confinement of electromagnetic waves in 3D layer-by-layer photonic crystals

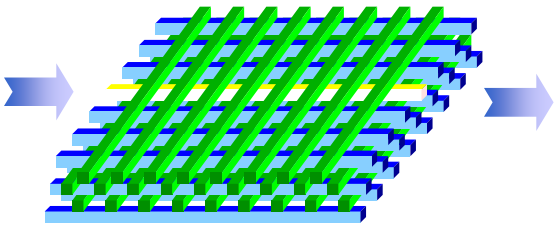
EXPERIMENTAL SETUP

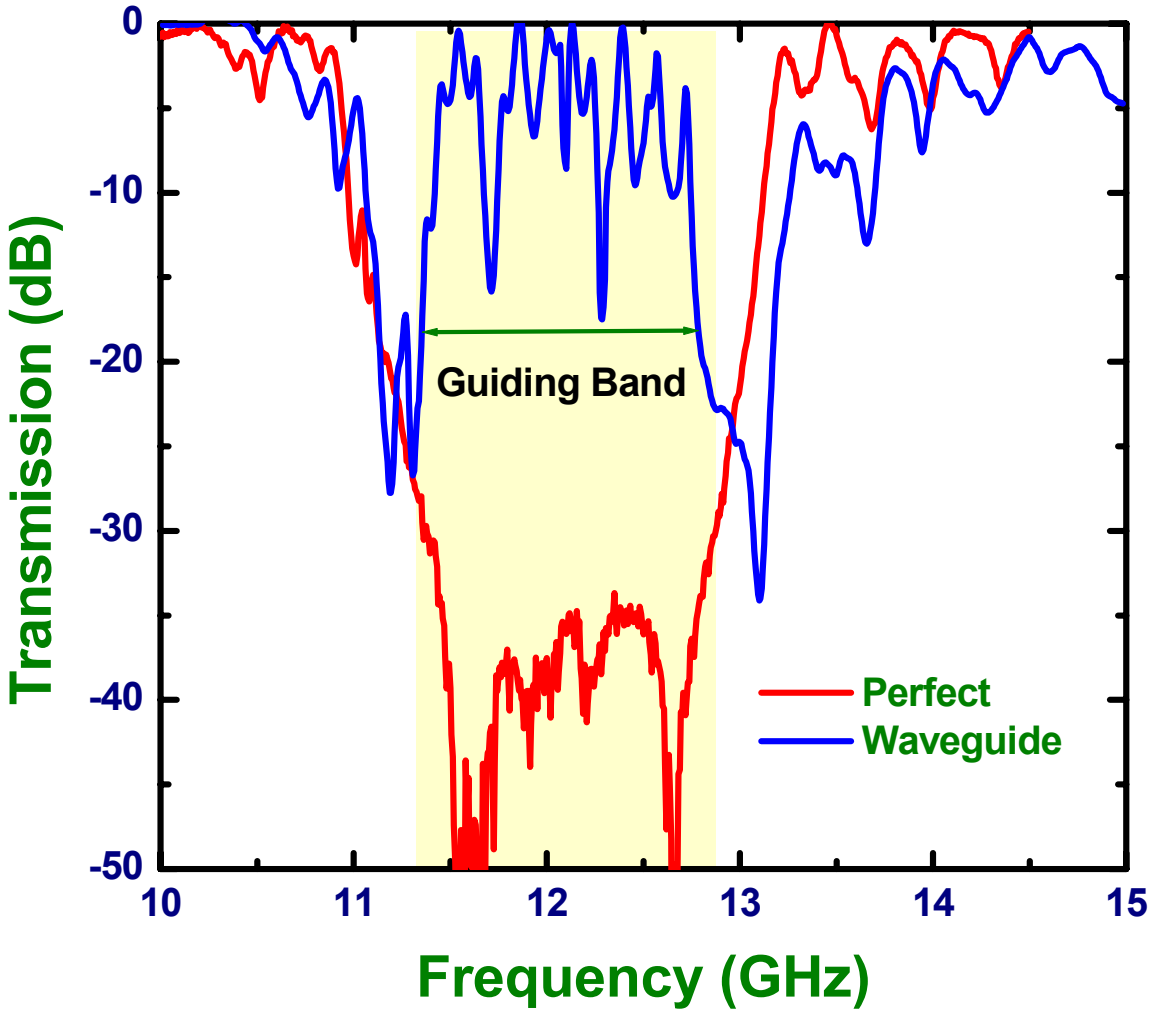


Symmetry: Face centered tetragonal (fct)
Material: Alumina of refractive index
ε =3.1 at microwave frequencies
Dimensions: 0.32 cm × 0.32 cm × 15.25 cm
Photonic band gap: 10.6 GHz -12.8 GHz



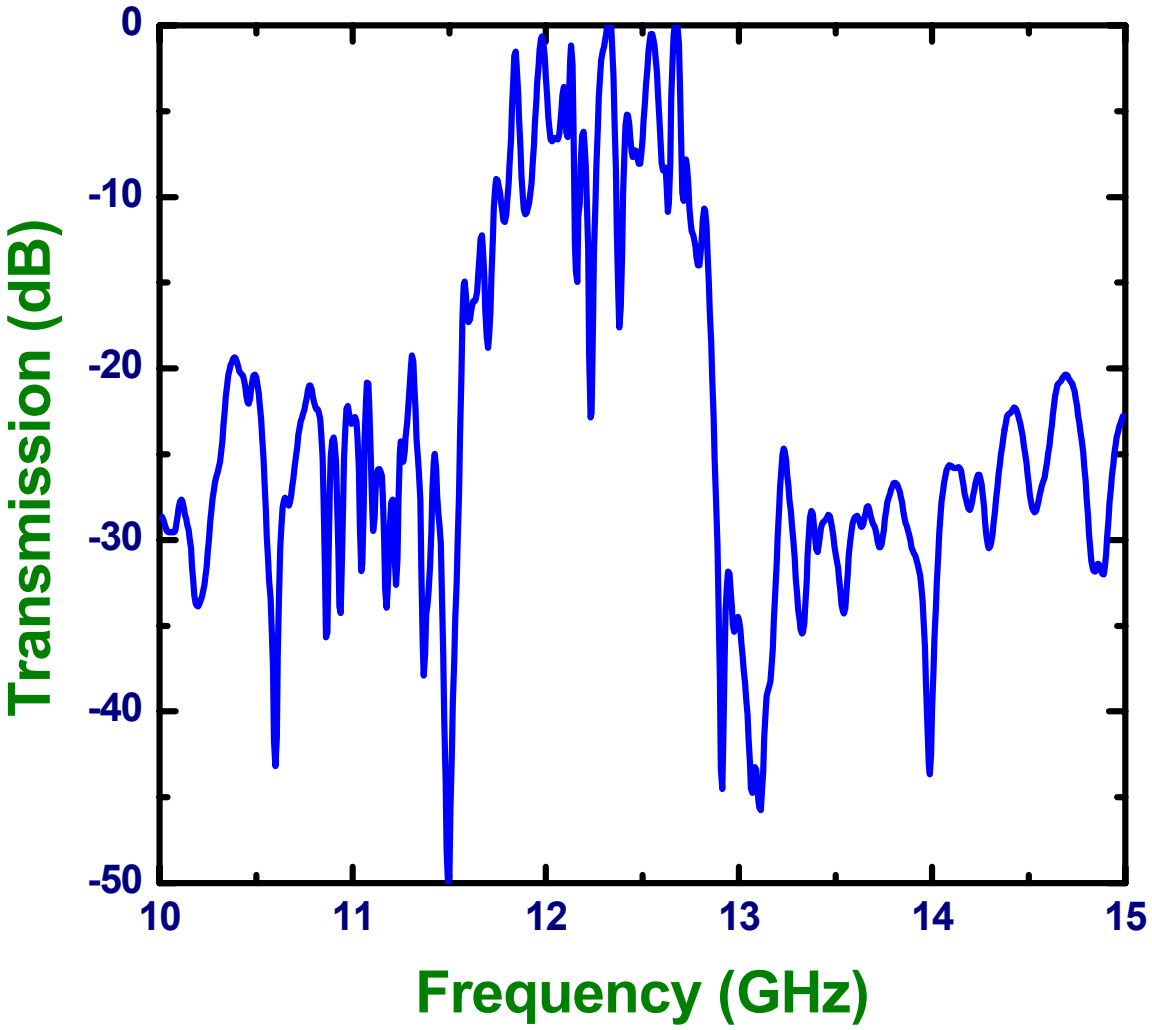
STRAIGHT WAVEGUIDE

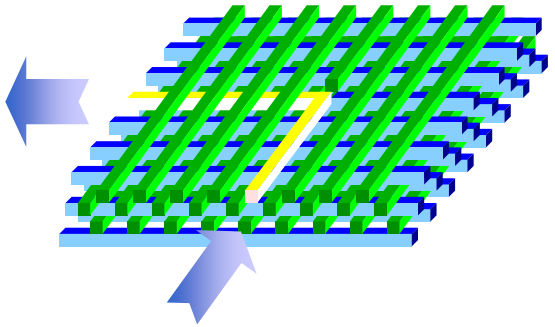




- Nearly full transmission was achieved for certain frequencies
- The full transmission within the waveguiding band was a proof of how well the wave was confined and guided without lossess

WAVEGUIDE BENT



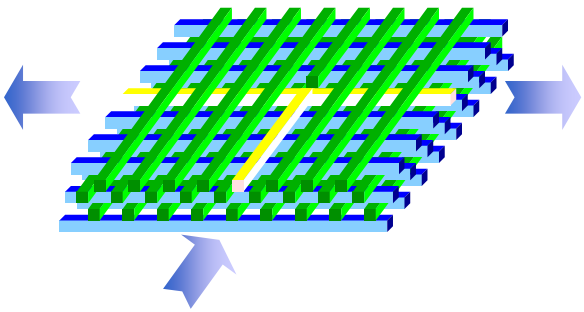


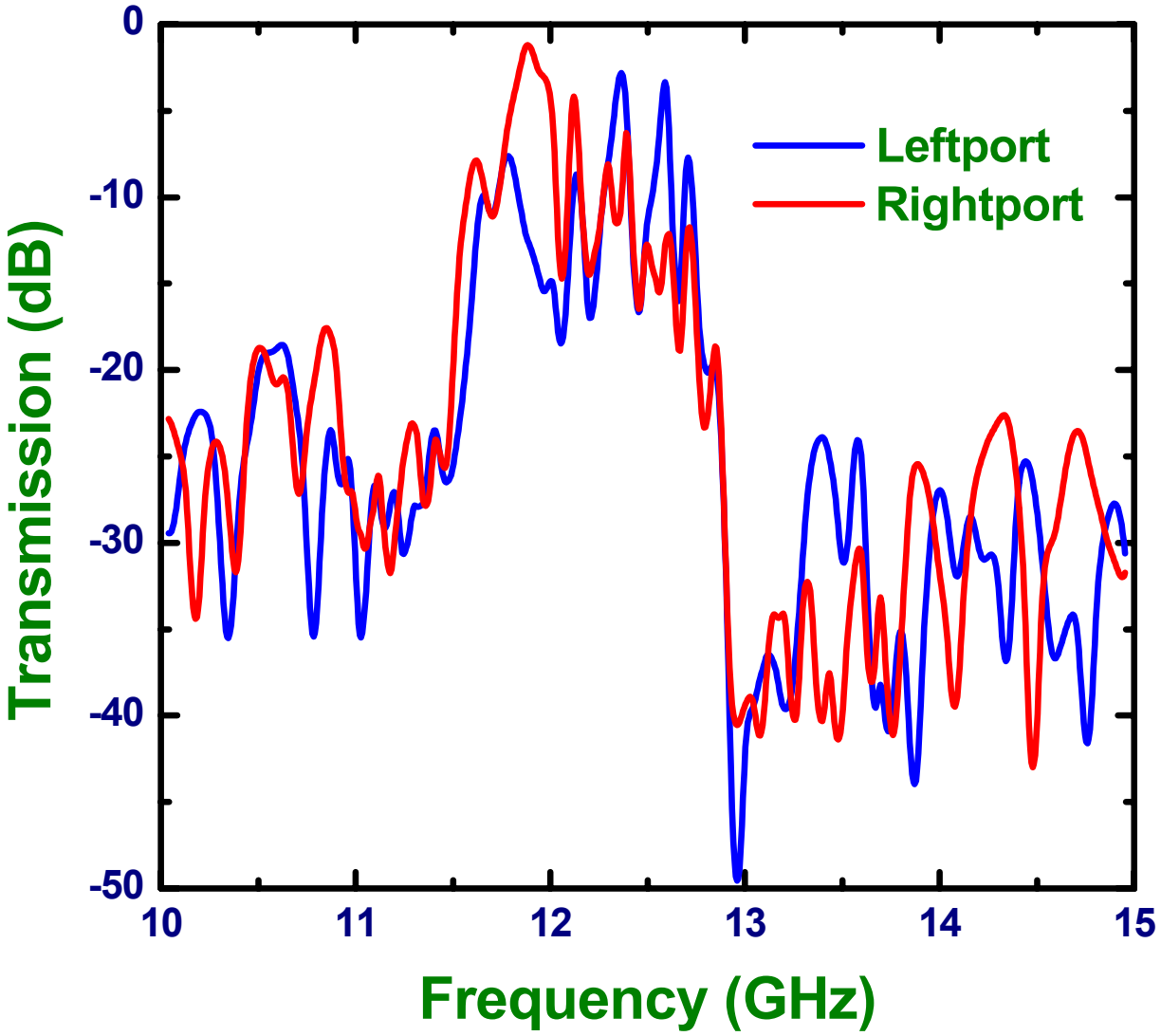
Comparison with simulation [Noda's Group, APL (1999)]:

The bending band covers 68% of the stop band which is very close to the simulation results value of 67%.

- The full transmission through a 90° bent was achieved for certain frequencies throughout the waveguiding band

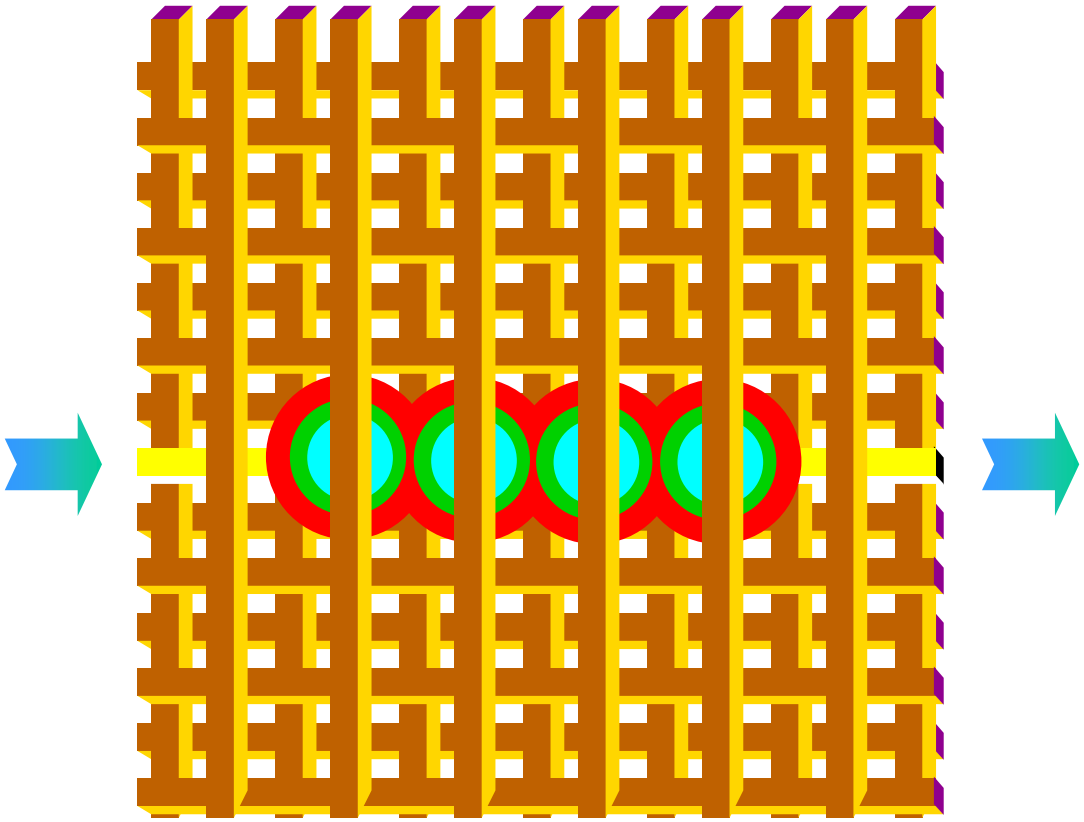
POWER SPLITTER





- The electromagnetic power in the input port splits into the two output ports throughout the guiding band

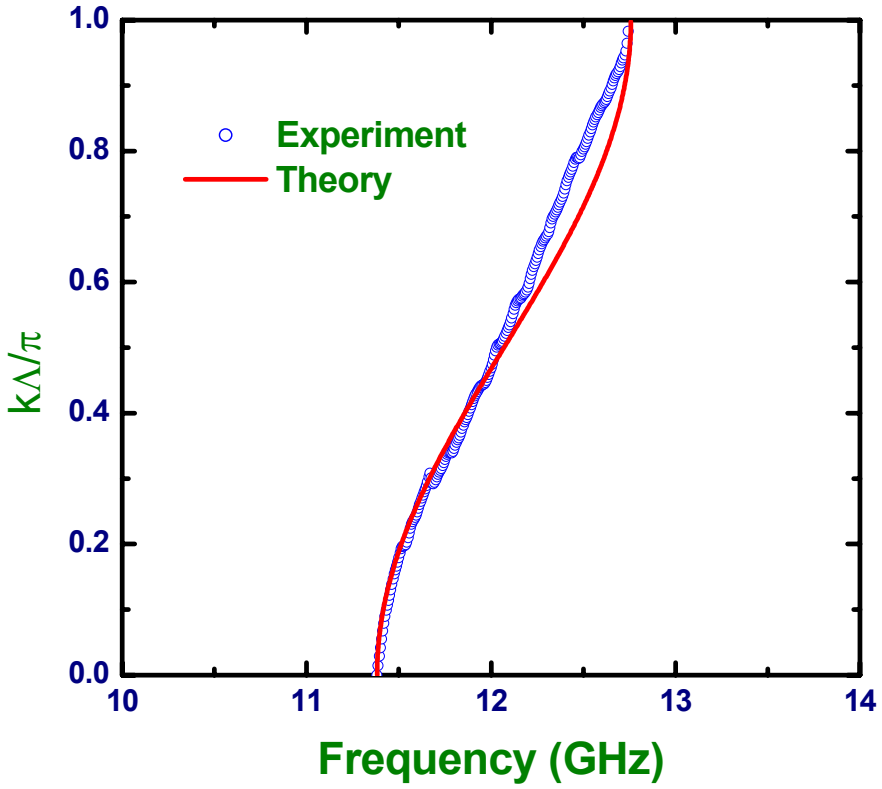
THEORETICAL MODEL: TIGHT BINDING APPROXIMATION

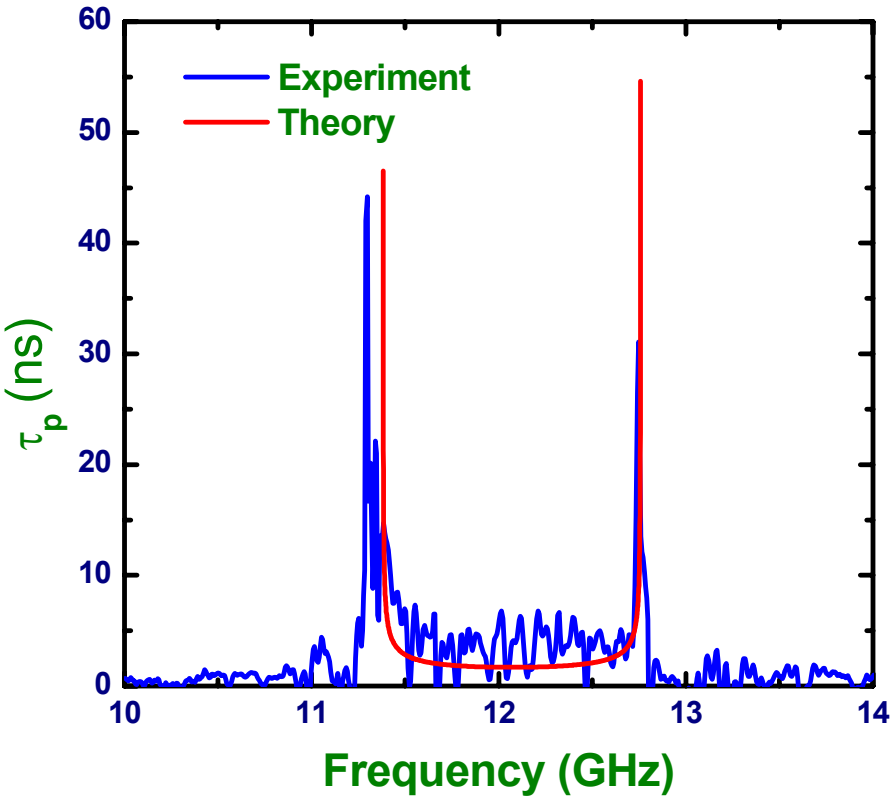


Each vacancy just below the removed rod behaves as a boxlike cavity

- The coupling between these localized cavity modes allows propagation of photons by hopping through the vacancy of the missing rod

DISPERSION RELATION & PHOTON LIFETIME



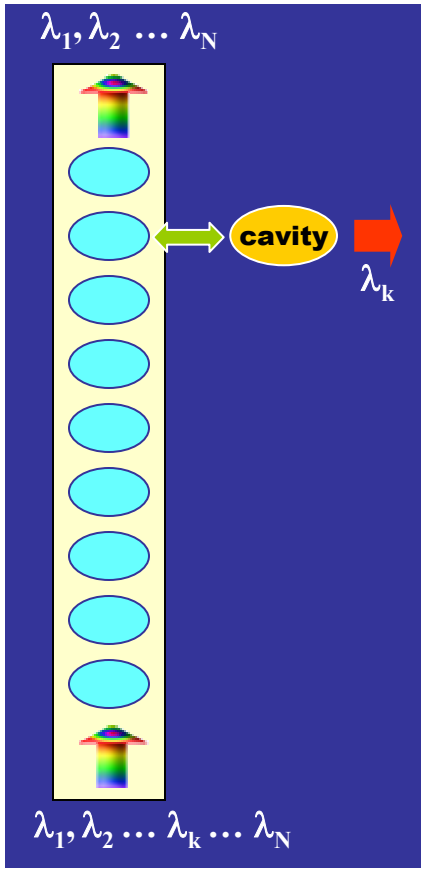


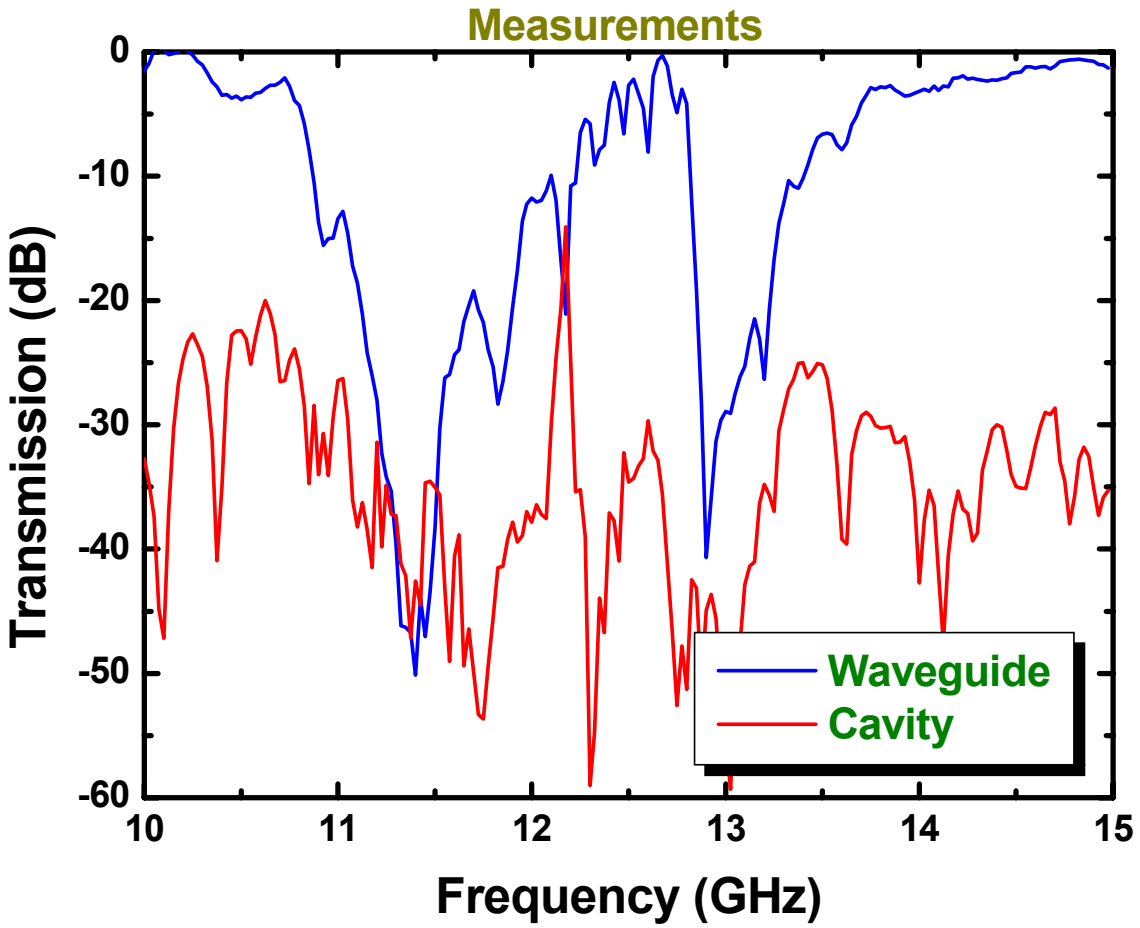
$$\omega(k) = \Omega\left(1 + \kappa \cos(k\Lambda)\right)$$

$$\tau_p(k) = L/v_g(k) + 2\pi L/c$$

- Experimental results were in good agreement with the tight-binding approximation predictions

WDM APPLICATIONS: DROPPING A SELECTIVE WAVELENGTH



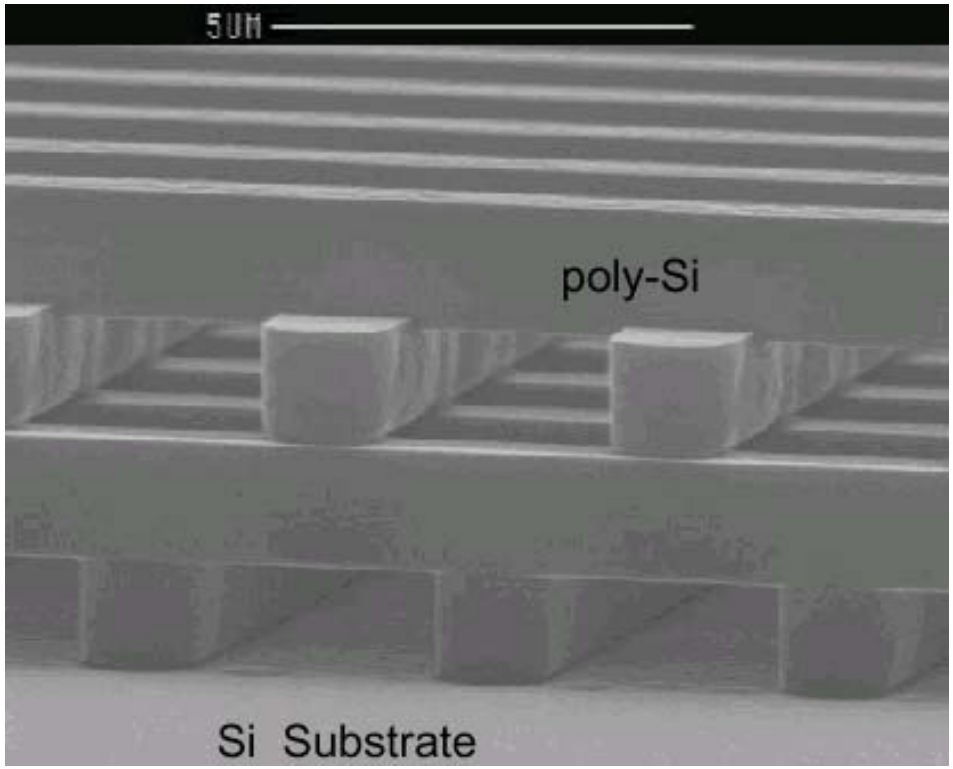


Bayindir and Ozbay [in preparation]

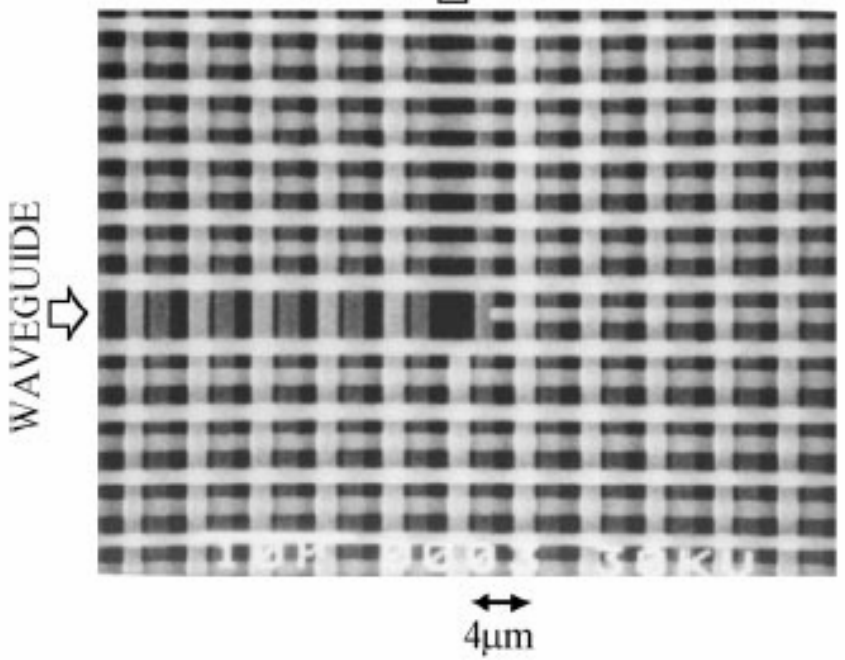
- Electromagnetic wave with a specific frequency can dropped from the guided mode inside the waveguide.
- Tunability can achieved by changing properties of the cavity.

3D LAYER-BY-LAYER STRUCTURES AT OPTICAL WAVELENGTHS

Lin *et al*, Nature **394**, 251 (1998)



Noda *et al*, Science **289**, 604 (2000)



- **Highly confined waveguides, waveguide bends, power splitter, add-drop filters, switches can be used in future ultrasmall optoelectronic integrated circuits.**

SUMMARY

- Various applications of 1D, 2D, and 3D coupled-cavity structures were demonstrated
- The tight-binding approximation was successfully applied to the photonic structures
- The finite-difference-time-domain (FDTD) and the transfer matrix method (TMM) results agree well with our measurements

ACKNOWLEDGEMENTS

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MORE INFORMATION

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